Wisconsin Highway Research Program

The Effect of Fine Aggregate Angularity, Asphalt Content and Performance Graded Asphalts on Hot Mix Asphalt Performance

Anthony D. Stakston and Hussain Bahia
University of Wisconsin - Madison
Department of Civil and Environmental Engineering
October, 2003

WHRP 03-04

The Effect of Fine Aggregate Angularity, Asphalt Content and

Performance Graded Asphalts on Hot Mix Asphalt Performance.

WisDOT Highway Research Study 0092-45-98

By

Anthony D. Stakston, Research Assistant
Hussain U. Bahia, Associate Professor
University of Wisconsin – Madison
Department of Civil and Environmental Engineering
1415 Engineering Drive, Madison, WI 53706-1490

Submitted to

October 2003

DISCLAIMER

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-45-98. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

ACKNOWLEDGEMENTS

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. WHRP 03-	2. Government Accession No.	3. Recipients Catalog No.

4. Title and Subtitle	5. Report Date
The Effect of Fine Aggregate Angularity, Asphalt Content and Performance Graded Asphalts on Hot Mix Asphalt Performance	May 2003
	6. Performing Organization Code 0092-45-98

7. Author(s)	8. Performing Organization Report No. WHRP 03-
H.U. Bahia, Associate Professor and A. Stakston, Research Assistant	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
University of Wisconsin – Madison Department of Civil and Environmental Engineering 1415 Engineering Drive Madison, WI 53706-2507	**11. Contract or Grant No.** WisDOT SPR# 0092-45-98

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Wisconsin Department of Transportation Division of Transportation Infrastructure Development Research Coordination Section 4802 Sheboygan Ave., Box 7065, Madison, WI 53707-7910	Final Report, 200-2003
	14. Sponsoring Agency Code

15. Supplementary Notes

6. Abstract: The Wisconsin Department of Transportation (WisDOT) has implemented the Superpave recommendations in the 2000 Supplemental Specifications. This research was directed towards better understanding of the influence of angularity of fine aggregates, asphalt content, and performance grade of asphalts on hot mix asphalt (HMA) performance. Aggregates from four sources across the state of Wisconsin were used in this study. Each source provided two blends that vary in gradation: (1) a fine blend and (2) an S-shaped blend. Testing was accomplished using the Superpave gyratory compactor (SGC) and a device that fits inside of the SGC known as the gyratory load plate assembly (GLPA). Mixture densification and performance indices were calculated based on the data obtained from both the SGC and GLPA. Two indices reported data relating to the construction compaction phase of the gyratory compaction (initial stage) and two indices related to the traffic densification stage (later stage). Volumetric properties such as %G_{mm} @ N_{init}, %G_{mm} @ N_{des}, %G_{mm} @ N_{max}, and VMA were also reported.

The results of this study do not support the assumption that higher values of FAA would always result in better performing mixtures. The findings show the effect of FAA to be highly dependent on the source of the aggregates and their gradation. For certain blends of aggregates the laboratory compaction data show adverse effect of angularity on mixture resistance to shearing. It is therefore difficult to suggest a limit on FAA independent of the source or gradation that would improve quality of asphalt mixtures. The results of this study confirm earlier findings that varying the asphalt content has an important influence on critical properties of HMA mixtures, which include volumetric and frictional resistance of mixtures. The effect is found to be highly dependent on the source of the aggregate. The effect of asphalt content is found to be more important during the initial stages of compaction compared to the final stages for the majority of the blends tested in this study. The results indicate that the new parameters selected (CEI and TEI) are sensitive to asphalt content and follow the known trend of changes. Because of this sensitivity, they show the potential of complimenting the volumetric properties in selecting a mixture design that would result in good performance. The results of this study indicate that varying the performance grade of the asphalt has an important influence on certain critical properties of HMA mixtures. The effect is found to be highly dependent on the source of the aggregate. The effect of the performance grade is found to be more important during the final stages compared to the initial stages of compaction for the majority of the blends tested in this study. Because of the lack of trends between FAA values and the indices measured in this study, it is recommended that actual testing of the mixture with the selected asphalt be conducted and that the selection be based on the results of CEI, TEI, and volumetrics.

17. Key Words	18. Distribution Statement
Asphalt Mixtures, Gyratory Compactor, Fine Aggregate Angularity, Performance Grade, Aggregate Gradation, Volumetric Properties.	No restriction. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages:	22. Price
Unclassified	Unclassified	148	

TABLE OF CONTENTS

CHAPTER ONE
BACKGROUND

This chapter includes a summary of the literature review conducted on the requirements for fine aggregates and asphalt binders, the cause of permanent deformation, test methods used to determine required properties, and current recommendations for fine aggregate angularity used by different State Highway Agencies. The chapter concludes by defining the specific problem addressed in this study.

1.1 Asphalt Mixture Requirements

Superpave procedures include specifications and recommendations for material properties of both the asphalt cement and fine and coarse aggregates used in hot mix asphalt (HMA). Aggregate properties specified include fine and coarse aggregate angularity, flat and elongated particles (for coarse aggregate) and sand equivalency (for fine aggregate). Asphalt cement requirements include the asphalt content and the asphalt performance grade. Of particular interest for this research are the fine aggregate angularity requirements and the possible interactions with asphalt content and performance grade.

1.1.1   Current Angularity Requirements for Fine Aggregates

Superpave has defined limits on the angularity of fine aggregates used in HMA using the National Aggregate Association (NAA) test, Method A (also exists as AASHTO TP 33). The purpose of these limits is to increase the mix's ability to resist excessive permanent deformation or rutting under traffic loading. The previous Superpave limits were dependent on how much traffic the pavement is designed for (Equivalent Single Axle Loads, ESALS)

and the depth from the surface of this layer that the mixture is designed for. Table 1.1 shows

the original Superpave requirements for Fine Aggregate Angularity (FAA).

Table 1.1 Superpave Fine Aggregate Angularity Requirements (33) and the Wisconsin

Traffic	Original Superpave Specification		Wisconsin Dot Specification
ESALS (millions)	<100 mm	>100mm	AASHTO T304, Method A
< 0.3	-	-	40
< 1	40	-	40
< 3	40	40	43
< 10	40	40	45
< 30	45	40	45
>= 30 <100	45	45	45
>100	45	45	
SMA			45

In 2000, new updated FAA limits were implemented in which the table was

simplified by removing the depth categorization and adding more traffic categories. This

new version was adopted in Wisconsin in the 2000 edition of the State of Wisconsin

Supplemental Specifications. Table 1.2 shows the new Wisconsin Department of

Transportation (WisDOT) requirements for fine aggregate angularity.

Table 1.2 WisDOT Fine Aggregate Angularity Requirements (68)

Traffic ESALS (millions)	Fine Aggregate Angularity
< 0.3	40
0.3 - < 1	40
1 - < 3	43
3 - < 10	45
10 - < 30	45
> = 30	45
SMA	45

1.1.2 Current Asphalt Content Requirements

Superpave procedures, similar to other asphalt mixture design methods, require using the Superpave Gyratory Compactor (SGC) to determine a design asphalt content for each aggregate blend. The determination of the design asphalt content is based on measuring density changes as a function of number of gyrations (compaction effort) in the SGC and satisfying the required density at three reference points. These points include Ninitial, Ndesign, and Nmax (Initial, design, and maximum number of gyrations). The number of gyrations required varies according to traffic. Similar to the FAA requirements, the density limits are intended to increase the mix ability to withstand permanent deformation or rutting, and raveling. The design asphalt content is known to vary depending on aggregate gradation, angularity, absorption , and viscosity of the asphalt binder. In implementation of the selected design asphalt content, a slight variation is accepted to allow for the inherent variability in the production and handling of the asphalt mixture during construction. The allowable variation is a matter of quality control and it varies from one specification to another. Currently, the Wisconsin Department of Transportation has the limits of +/- 0.5% of the optimum asphalt content as the allowable range in design asphalt content (68).

1.1.3 Current Performance Graded Asphalt Requirements

Superpave specifications require selecting the performance grade of the asphalt cement based on climate and traffic speed. The climate is included through calculating the pavement design temperature using air temperature and solar radiation estimated from location. The effect of traffic speed is considered in a less quantitative method. Currently, he National Center for Asphalt Technology (NCAT) suggests increasing the performance

grading of a given asphalt by one grade for slow transient loads (intersections), and two grades for stationary loads (bus stops). The state of Wisconsin also includes increasing the performance grading for traffic volume. Currently the performance grade is increased one grade for traffic volume over 10 ESALs (Equivalent Single Axel Loads).   The purpose of this performance grade increase is to increase the mix's ability to withstand permanent deformation or rutting. The performance grading increase in asphalt cement is dependent on the traffic speed, and how many ESALs the pavement is designed for when being planned.

1.2   Causes of Permanent Deformation

A review of the literature regarding the subject of permanent deformation indicates that the phenomenon is complex. Studies cite multiple causes for rutting including: (1) aggregate gradation, (2) aggregate absorption, (3) aggregate affinity for asphalt, (4) aggregate size, (5) coarse aggregate shape, (6) coarse aggregate texture, (7) fine aggregate shape (angularity), (8) mineral filler properties, (9) asphalt content, (10) performance grading, (11) plastic fines in the fine aggregate, and (12) performance graded asphalts (3, 5, 13, 19, 23, 28, 29, 42, 46, 20, 2, 30, 24, 60, 63, 64, 66). The above list illustrates that there are many different factors that can cause or contribute to rutting. From this list, however, some factors appear to have a more significant impact than others.

Another study cited low in-place voids, meaning a low air void percentage in the pavement, as the primary cause of rutting (5), although this could be thought of as a symptom of the mix design and constituents rather than a cause.

The general factor that most consistently was cited as influencing rutting was aggregate properties. A study by Button, Perdomo, and Lytton found nine possible causes of

rutting, but stated that the aggregate characteristics were the primary material quality factor influencing rut susceptibility (3). Two other studies more specifically addressed the type of fine aggregate used as the greatest influencing factor on stability (44, 48). Of all the properties of aggregates that were examined in the literature, two primary characteristics emerged: (1) gradation and (2) angularity. Gradation was cited in 4 studies (19, 23, 29, 42) as being of significant importance in rut prevention. Dukatz even indicated that rut resistance is "highly dependent upon aggregate grading" and that mixes made with the best possible materials will fail without the proper gradation (42). The evidence that angularity influences rut susceptibility was even more compelling (42).

The angularity factor of an aggregate used in HMA can be divided into two parts: (1) the angularity of the coarse aggregate portion and (2) the angularity of the fine aggregate portion. Several studies did not distinguish between fine and coarse, but simply cited angularity as the primary concern regarding rutting and stated that the aggregate angularity has a "major effect on stability" (25) and that high angularity provides "much more resistance to permanent deformation" (18). Other studies did compare the relative effects of fine aggregate angularity and coarse aggregate angularity. One by Moore and Welke states that both the angularity of the fine aggregate and the overall gradation are important factors, but that the angularity of the coarse aggregate is not as important (28). Another study determined that there was a "strong relationship" between the fine aggregate angularity and rutting and a "weak relationship" between the coarse aggregate angularity and rutting (46). The literature, therefore, suggests that angularity is important, and that the angularity of the fine aggregate portion is a critical part of angularity.

Establishing the importance of the angularity of the fine aggregate can be done by

looking at the studies which addressed sands (fine aggregates) in HMA. A study by Kalcheff compared several HMA mixes made with manufactured sand (that typically has high comparative angularity) with others made with natural sand (that typically has a lower comparative angularity). In all cases, the mixes with the manufactured sand had "improved mixture behavior over those with only natural sand" (18). Another study states simply that too much natural sand in HMA leads to rutting (13). Two similar studies reported that replacing natural sand with manufactured sand had the greatest effect on stability. A study by Meier states that Hveem stability is linearly related to fine aggregate shape and surface texture (25), while another study states that increasing the angularity of sands will contribute to reducing rutting (41). It is important to note that existing literature also points out that although fine aggregate angularity plays an important role, other factors should still not be ignored (23, 28). These studies point to gradation as having an interactive effect with angularity in determining rut susceptibility of a mix.

One of the factors that stands out in importance in binder properties is asphalt content. Asphalt content in excess of the optimum level may lead to problems like flushing, and insufficient air-voids space may yield a reduction in stability. On the other hand, asphalt contents below the optimum will jeopardize the long-term durability of the mixture and will produce a harsh mixture that complicates lay-down and construction operations (63). One study indicates that asphalt content may be more important than gradation or angularity in determining performance. (62). The authors of the Hot Mix Asphalt Materials, Mixture Design and Construction by NCAT states probably the single largest contributor to rutting in HMA is excessive asphalt content (33).

Changing the asphalt content of a HMA mixture can cause Numorous problems. "An HMA pavement can ravel or crack if it is deficient in asphalt content by as little as ½ percent, whereas ½ percent excessive asphalt content can cause flushing and rutting" (65).

The other major factor affecting rutting in binder properties is the performance graded asphalts. Establishing the importance of the performance graded binders can be done by looking at two areas: (1) performance grades (PG), and (2) modified binders.

A study by University of Nevada-Reno compared HMA mixtures by adding a polymer-modified asphalt compared to an unmodified asphalt. The polymer-modified asphalt increased in performance grades compared to the unmodified asphalt. The polymer-modified asphalt resulted in significant reduction in the permanent deformation (rutting) of the HMA mixture (60). Another study by Kamel, and Miller compared pavement performance containing conventional and engineered (modified) asphalts. The use of modifiers created higher grades of performance graded asphalts that provided rutting reductions of up to 50 percent and an increase in pavement load-carrying capacity of more than 300 percent (63). The susceptibility of the HMA mixture decreased for all but one of the six performance graded binders compared to the grade below used in a field study on Interstate 80 in Wyoming by the Materials Branch of the Wyoming Transportation Department (66).

1.3   Current Recommendations Used in Practice

1.3.1   Fine Aggregate Recommendations

In light of the literature available on permanent deformation, several states and organizations have imposed guidelines or recommendations to control rutting. In general, many highway agencies limit the amount of natural sand that can be used in HMA (19, 20).

A previously mentioned study by Button, Perdomo, and Lytton identified 9 possible causes of rutting, and determined that the best way to reduce it was to limit the amount of natural sand to 10-15% of aggregate weight (3). Three other studies agree that the amount of natural sand should be limited to 15-30%, depending on road usage level (6, 7, 43). The Indiana DOT has recently increased the % fracture requirement of both their coarse and fine aggregate to 95% because of rutting concerns (34). Similarly, Kansas requires that 50-85% of aggregates (depending on road usage level) used in HMA be crushed (6). Minnesota set its guidelines in terms of FAA, requiring that the FAA be above 45 for all mixes (36). This is more restrictive than the SUPERPAVE requirements of 45 for highly traveled roads and only 40 for lightly traveled roads. The WisDOT currently limits the amount of natural sand that can be used in a mix to 20%. This matches the recommendations of the Federal Highway Administration (FHWA) at a 20% maximum. In Europe, current recommendations are that a minimum of 50% manufactured sand be used in all mixes (43).

1.3.2   Asphalt Content Recommendations

In light of the literature available on permanent deformation, several states and organizations have imposed guidelines or recommendations to control rutting. In general, many highway agencies limit the range of asphalt content that can be used in HMA (59). The WisDOT currently limits the range of asphalt content that can be used in the mix to +/- 0.5% of the optimum asphalt content (68).

1.3.3   Performance Graded Asphalt Recommendations

The present Superpave binder selection process by Federal Highway Association is based on climate and assumes that the HMA pavements will be subjected to fast moving traffic. However, significantly lower loading rates are experienced by HMA pavements at some locations such as intersections, and weigh stations. There are cases such as bus stops where loads are also stationary. In such cases of slower loading rates an asphalt binder must exhibit a higher stiffness to minimize rutting. To meet these situations, the high temperature grade should be increased by one grade for slow transient loads and by two grades for stationary loads (33). For example, Wisconsin uses primarily a PG 58-28 grade based on climate for fast moving traffic. A PG 64-28 grade would be used for a slow transient loads, and a PG 70-28 grade would be used for stationary loads. Therefore a PG 70-28 grade was selected for the experiment to compare versus the PG 58-28 selected by climate for fast moving traffic. The WisDOT currently allows the increasing (bumping) of the PG grade for traffic speed, and load.

1.4   Test Methods

1.4.1   Test Methods for Measuring Angularity of Fine Aggregate

Many test methods have been developed for determining the angularity of fine aggregates. Kandhal, Khatri, and Motter present a method of classifying these tests. They suggest that the methods be classified as either direct or indirect (20). A direct measurement would be when each particle is in some way measured (either qualitatively or quantitatively) to determine its angularity. An indirect measure is one that measures the properties of the fine aggregate blend and from that measure infers particle shape or texture information.

Based on the published literature, there are only three tests that have been used that could be considered as direct tests. The United States Army Corp of Engineers developed a direct method for testing the angularity of fine aggregates known as Method CRD-C 1535. This method uses a microscope to evaluate individual particles for flat or elongated properties as well as shape (20). The other direct method found is known as the Laughlin Method. This method uses enlarged photographs of fine aggregates to compute a roundness based on the shape of the particles (35). The third direct test method also determines particle shape from image analysis. This method was developed at the University of Arkansas (19) and is digitally-based. Other computer methods have been introduced recently. Two computer-automated procedures, which make use of the advances in digital- image processing, to quantify fine aggregate angularity, are presented by Masad and co-workers (70). The first method relies on the concepts of the erosion-dilation techniques. This consists of subjecting the aggregate surface to a smoothing effect that causes the angularity elements to disappear from the image. Then, the area lost as a result of the smoothing effect is calculated and used to quantify angularity. The second method is based on the fractal approach. Image-analysis techniques are used to measure the fractal length of aggregate boundary. The fractal length increases with aggregate angularity. None of the methods measure the surface texture, which is recognized to contribute to angularity.

The indirect test methods are far more numerous, although the majority of them may be defined as flow tests. Those not included in the flow test category include the direct shear test and the Florida Bearing Ratio. The Direct Shear Test relies on a test borrowed from soil mechanics that tests the resistance of the aggregate to a shear failure. The theory behind this test is that the more angular the aggregate particles are, the higher the resistance to shear

failure caused by the increased aggregate interlock. The results are given as an internal friction angle (20, 25). The Florida Bearing Ratio uses the materials ability to support a load as an indication of its angularity (25).

The different flow tests all are very similar. Flow tests cause the fine aggregate being tested to flow through a funnel into a cylinder. The results of these tests are reported either in terms of time or mass. The theory behind reporting the results in terms of time is that the time it takes for a sample of aggregate to flow through the cone will be directly proportional to the angularity of the sample. The theory behind reporting the results as a mass is that if the cylinder into which the sand flows has a known volume, and the density of the aggregate is known, then the mass of the filled cylinder will depend only on the angularity and surface texture. The higher the angularity and surface texture of the aggregate, the more air voids will be trapped in the sample between individual aggregates, leading to a lower mass for the cylinder. Conversely, if the angularity of the sample is low, the material will compact as the cylinder fills, more material will then be able to fit in the cylinder (without overflowing), and the cylinder will have a higher mass.

There are several flow tests used to measure the angularity of fine aggregates. ASTM D3398 separates the original material into several distinct sieve sizes before testing. The test is then run on each sieve size and the mass of material retained in the cylinder is recorded. Results are computed using a weighted average based on the original gradation (20). The New Zealand Method uses the original sample without any sieving. Flow time is measured and the results recorded (28). The National Crushed Stone Association (NCSA) Method separates the material into three sieve sizes. The three sizes are tested individually, and flow time is measured (7, 25). The Virginia method uses the same technique as the NCSA

Method (22). The National Sand and Gravel Association (NSGA) Method breaks the

material down into four sieve sizes. The sizes are then recombined and tested to report the

required time (20). The Ishai and Tons Method compares the sample against a standard test

medium of glass beads (14). The Specific Rugosity by Packing Volume Test is another flow

test that gives a value of specific rugosity instead of angularity (40, 25, 34).   The Void Ratio

by Western Technologies and the Rex and Peck Time Index are two other flow tests (25).

The most widely used flow test in the asphalt area is the National Aggregate

Association (NAA) test. The NAA test is a flow test that could be conducted according to

three protocols. All three protocols measure the mass of material retained in the cylinder as

an indicator of aggregate angularity. One of the methods uses the material "as is", and the

other two methods require sieving the material into different sizes and creating a "standard

gradation" with the constituents for the test.

1.4.2   Test Methods for Measuring Asphalt Content

The asphalt content of a mixture is measured by an extraction test (ASTM D2172) or

with a nuclear gauge (ASTM D4125). The nuclear gauge is used to measure asphalt content

much the same way as it is used to measure moisture in soils. The extraction test involves

adding a chemical solvent to the asphalt mixture to dissolve the asphalt cement. The asphalt

cement and solvent are then passed through a piece of filter paper, but the aggregate is not

allowed to pass. This is not highly accurate test but it is widely used for measuring asphalt

content.

NCAT has developed a test method to determine the asphalt content of the HMA

mixtures by ignition. In the NCAT ignition method, a sample of HMA mixture is subjected

to an elevated temperature of 538° C (1000^oF) in a furnace to ignite and burn the asphalt

content from the aggregate (69). NCAT's work has resulted in a test procedure and

equipment that automatically measures the asphalt content in 30-40 minutes.

1.4.3 Test Methods for Measuring Performance Graded Asphalts

The Superpave asphalt binder specification (AASHTO MP1-93) is a standardized

table used by most state Departments of Transportation. The test equipment measures the

physical properties included in the specification. The test equipment used in the binder

specification are Rolling Thin Film Oven (RTFO), Pressure Aging Vessel (PAV), Rotational

Viscometer (RV), Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), and

the Direct Tension Tester (DTT). The physical properties tested by the equipment remain

constant for all performance grades (PG), but the temperature at which these properties must

be achieved varies from grade to grade depending on the climate in which the asphalt grade

is intended for use in an environment where an average seven-day maximum pavement

temperature of 58^oC (Wisconsin) and a minimum pavement design temperature of -28^oC

(Wisconsin), are likely to be experienced.

1.5 Wisconsin Fine Aggregates

A survey was conducted by the Wisconsin Department of Transportation (WisDOT)

regarding the types and characteristics of fine aggregates in the state (Appendix A). The

survey identified 24 manufactured sands, 14 natural sands, and many blends of sands to be in

use by the asphalt contractors in Wisconsin. Figure 1.1 shows the fine aggregate angularity

values for the natural and the manufactured sands in the state.

Figure 1.1 shows that there are no natural sands with a fine aggregate angularity

greater than 43 and no manufactured sands with a fine aggregate angularity less than 43.

Also, of all the natural sands tested, only one had a fine aggregate angularity value of less

than 40 (39.8). There were, however, several blended sands that had fine aggregate

angularities below 40 (not shown in Figure 1.1).
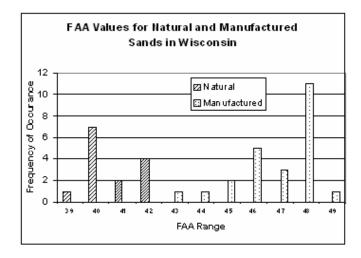
Figure 1.1 Fine Aggregate Angularity of Sands in Wisconsin (57)

1.6   Methods of Assessing the Importance of Angularity, Asphalt Content, and Performance Grading on Mixture Performance

For the purpose of this research, performance is defined by the ability of a mix to

resist rutting. This definition of performance is well supported in the literature. (3, 5, 6, 13,

23, 29, 54, 55).

A loaded wheel tester was used in several studies in the literature to determine the

performance of the HMA (13, 23, 54). This test is a rutting test that uses a small wheel to

apply a repetitive load to a sample, simulating traffic loading. A deep rut depth, or a fast

rutting rate, indicate that the sample is not very rut-resistant. Hveem stability, indirect

tension, unconfined compression, static creep, and dynamic creep were all used in one study

(3). That study was performed on samples that had all failed in the field. The United States

Army Corps of Engineers gyratory testing machine was used in two studies to test the

performance characteristics of the HMA (5,6). Both studies used the Gyratory Elasto-Plastic

Index (GEPI) as a response variable. The study by Cross and Brown (5) also used voids in

the total mix (VTM), voids in the mineral aggregate (VMA), and final test head roller

pressure (RP) as response variables. Of the response variables used in that study, "the shear

stress to produce 1 degree gyration angle as indicated by the gyratory testing machine roller

pressure (RP) gave the single best correlation with rate of rutting." (5)

The research performed in this study also uses a shear stress measure determined

from a gyratory testing device as a response variable. It was conducted using the gyratory

load cell plate assembly (GLPA). In another study conducted by this research group (11), the

GLPA was proposed as a means of determining the frictional resistance (resistive effort, w)

of a HMA sample during compaction in the SGC. The GLPA itself is made of two hardened

plates with three load cells between the plates. The GLPA is placed on top of a HMA

specimen during compaction in the SGC. In this configuration, the GLPA is able to record

the resultant force on the sample and the radial eccentricity throughout the compaction. The

resultant force and the eccentricity are used to estimate the resistive effort of compaction

using Equation 1.1

$$w = 4*e*P*\theta/(A*h)$$

where: w = resistive effort
      e = eccentricity of resultant
      P = magnitude of resultant
      θ = angle of gyrations (1.25^{o})
      A = area of cylinder
      h = height of specimen at given gyration

A typical example of the compactive effort as a function of the number of gyrations in the

gyratory compactor is shown in Figure 1.2
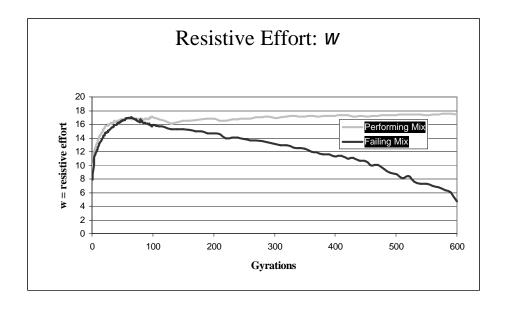
Figure 1.2 Sample Resistive Effort Curve.

1.7 Summary

As shown previously in this paper, there is a correlation based upon the literature

review between the angularity of fine aggregates, asphalt content, and performance grade

used in HMA mixes and the performance that can be expected from those mixes.

Superpave sets limits on the angularity of fine aggregates used in HMA to be a

minimum of either 40 or 45 depending on traffic and depth from surface. The Wisconsin

Department of Transportation (WisDOT) currently did not follow the Superpave fine aggregate angularity requirements until year 2000, opting instead to simply limit the maximum amount of natural sand permitted in mixes to 20%. In 2000 the department in a supplemental specification identified the limits shown in Table 1.1. From a scientific perspective, terms like natural sand or manufactured sand do not well define the properties of the materials. For example, it is possible to have a coarse natural sand that has a higher angularity than some semi-rounded manufactured sands (although this has not been found in Wisconsin). This may lead some to suggest that the state should change its specification from limiting the amount of natural sand to requiring a certain fine aggregate angularity. Very little is known, however, about how using sands that have various FAA values affect pavement performance the state of Wisconsin. The state has, therefore, little motivation to mandate that all mixes must have an angularity above 45. Another problem arises from the fact that there are very few sands in the entire state that fall below the angularity value of 40. Using this part of the Superpave specification would, therefore, greatly relax the current guidelines for some mixes. In other words, contractors would be free to use an unlimited amount of natural sand in the mixtures they produce.

Another complicating issue regarding Superpave's fine aggregate angularity specification is that it does not consider some important factors that may interact with the fine aggregate angularity to influence mixture performance. For example, the angularity of the fine aggregate may be more or less important depending on the overall gradation of the material used. It may also be influenced by the source of the aggregate. This research will attempt to begin to quantify some of these inter-relating variables as they affect mixture performance, including the source of aggregates and their gradation. An important goal of

this research is to provide additional information regarding what factors should be considered in selecting the angularity requirement of fine aggregates used in HMA in the state of Wisconsin.

Several states and organizations have imposed guidelines or recommendations to control rutting. In general, to control rutting many highway agencies limit the range of asphalt content that can be used in HMA. The limits are not dependent on any specific property. It is a standard used for all projects. Superpave requirement for asphalt content is +/- 0.5% of the optimum asphalt content. Currently, the Wisconsin Department of Transportation has the limits of +/- 0.5% of the optimum asphalt content.

The present Superpave binder selection process by Federal Highway Association is based on climate and assumes that the HMA pavements will be subjected to fast moving traffic. Currently, the National Center for Asphalt Technology (NCAT) suggest increasing the performance grading of a given asphalt by one grade for slow transient loads (intersections), and two grades for stationary loads (bus stops). In such cases of slower loading rates an asphalt binder must exhibit a higher stiffness to minimize rutting. To meet these situations, the high temperature grade should be increased by one grade for slow transient loads and by two grades for stationary loads (33). For example, Wisconsin is primarily a PG 58-28 grade based on climate for fast moving traffic. A PG 64-28 would be used for a slow transient loads, and a PG 70-28 grade would be used for stationary loads. The WisDOT currently allows the increasing (bumping) of the PG grade for traffic speed, and load.

1.8   Problem Statement

The current recommendations (see Table 1.3) for fine aggregate angularity, asphalt content and performance graded asphalts used in Superpave volumetric mixture design does not consider the possible interactions with aggregate source, aggregate gradation, fine aggregate angularity, asphalt content, and performance graded asphalts.

Table 1.3. Overview of Factors affecting Mixture Performance

Factors	Requirements (WisDOT)	Recommendations (WisDOT)	Test Methods
Fine Aggregate Angularity	Traffic Volumes	< E3 = 40 E3 – E30 = 45 > E30 = 50	AASHTO T304, method A
Asphalt Content	Standard Percentage	Optimum + / - 0.5%	ASTM D2172, Extraction Test
Performance Grading	Climate and Traffic	PG 58 – 28 (fast loads) PG 64 - 28 (slow loads) PG 70 – 28 (stationary loads)	AASHTO MP1-93, SUPERPAVE Asphalt Binder Specification

Although the limits are based on consensus, they could allow for inferior mixtures in Wisconsin if the effect of the limits and the interactions with other binder and aggregate characteristics are not determined. Quantifying the effect of fine aggregate angularity, asphalt content, and performance grade of asphalts on mixture characteristics is necessary for effective implementation of the Superpave recommendations.

CHAPTER TWO

RESEARCH METHODOLOGY

2.1   Hypothesis

Based on the literature review presented in the previous chapter, it has been concluded that the angularity of fine aggregates used in HMA has an effect on the HMA's performance. Numerous publications on this subject suggest that an increase in the angularity of fine aggregates will result in an improvement in the performance characteristics of asphalt mixes (13, 18, 23, 25, 28, 41). However, this finding is very broad and lacks details regarding the acceptable levels and how the other characteristics of a mix interfere with the effects of fine aggregate angularity (FAA) on mixtures. Aggregate source and aggregate gradation are expected to influence the way changes in FAA values affect the performance of the mix.

The main hypothesis of this research is that aggregate properties including shape, surface texture, gradation, and absorption of aggregates could interact to cause some HMA blends to be more sensitive to changes in FAA than others.

In addition to aggregate properties, it is well known that asphalt content and asphalt properties could have a significant effect on the performance of asphalt mixtures. Numerous publications suggest that a reduction of 0.50 percent of asphalt content will result in raveling or cracking if it is deficient in asphalt content, or can cause flushing and rutting if it has excessive asphalt content (59, 61, 62, 65). Moreover, numerous studies suggest that a change in grade performance will affect the sensitivity of the aggregate to raveling, cracking, and rutting (60, 63, 64, 66, 67). Since the objective of this research is to evaluate the effect of

FAA on the performance of mixtures, it is necessary to include in the experimental design the asphalt content and the asphalt grade to study the possible interaction of FAA with asphalt properties.

2.2   Controlled Variables

To study the combined effects of fine aggregate angularity, asphalt content, and performance grading, the following variables were included in the experimental testing program:

1.   Aggregate Source: Four different sources of aggregates were chosen for testing from four major asphalt contractors in Wisconsin. For the purposes of this research, they are referred to as sources W, X, Y, and Z.

2.   Blend Gradation: Two types of blends were tested for each source: (1) an S-shaped blend and (2) a fine blend. Figure 2.1 illustrates a coarse or S-shaped blend and a fine blend.

Example of Fine and S-Shaped Gradations

Fine
Gradation

Coarse
Gradation

% Passing
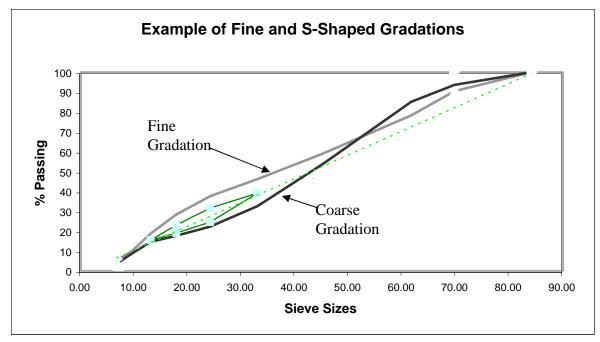
Sieve Sizes

Figure 2.1 Example of Fine and S-Shaped Gradations of Aggregate Blends. (% passing is by weight of total aggregates and Sieve sizes are in mm)

3.   Fine Aggregate Angularity (FAA): Four fine aggregate angularity levels were tested for each blend. These levels were produced by using 100% manufactured sand, 100% natural sand, and 40/60 and 60/40 blends.

4.   Asphalt Content (AC): Three asphalt contents were tested for each blend. These levels include optimum, optimum + 0.5%, and optimum – 0.5%. All mixes were tested at their individual optimum asphalt content (instead of a constant asphalt content for all mixes). This was done in order to simulate actual properties in the construction field.

5.   Performance Grading (PG): Two asphalts were used for each blend. The grades were PG 58-28 and PG 70-28.

The variables tested in this research are summarized in Table 2.1. The abbreviation MFGD stands for the manufactured sand. The ratios shown in the table refer to the ratio of manufactured sand to natural sand used in the mixtures.

Table 2.1 Research Scope

Type of Blend	Asphalt Content	Performance Grading	Aggregate Source			
			W	X	Y	Z
Fine Blend	Optimum - 0.5%	PG 58-28	100 MFGD 0 MFGD	100 0	100 0	
	Optimum		100 MFGD 60 / 40 40 / 60 0 MFGD	100 60 / 40 40 / 60 0	100 60 / 40 40 / 60 0	100 60 / 40 40 / 60 0
	Optimum + 0.5%		100 0	100 0	100 0	
	Optimum	PG 70-28	100 0	100 0	100 0	100 0
S-Shaped Blend	Optimum	PG 58-28		100 60 / 40 40 / 60 0	100 60 / 40 40 / 60 0	100 60 / 40 40 / 60 0
		PG 70-28		100 0		100 0

By changing the ratio of manufactured sand to the natural sand for each source, the fine aggregate angularity was altered, while keeping the other factors constant. This was achieved by separating the sands from each source into individual sieve sizes and then combining them to maintain the specific gradation for the blend from that source. The reference gradation used in each case was that recommended by the contractor.   The method of varying sand proportions allowed for the widest possible range of fine aggregate angularity values to be tested for each blend.

2.3 Response Variables

        The performances of mixtures were evaluated by measuring densification of the mixtures as well as shear resistance during the densification process. The details of these measurements are explained in the sections below.

2.3.1   Densification

        This research builds on a previous study conducted by the Asphalt Group at the University of Wisconsin-Madison. The study, entitled "Optimization of Constructibility and Resistance to Traffic: A New Design Approach for HMA Using the Superpave Compactor" (55), introduced several new concepts regarding interpretation of data obtained from the Superpave Gyratory Compactor (SGC). The primary contribution of the previous study was the introduction of the concept of breaking down the compaction curve into two sections, one representing construction compaction and the other representing traffic densification (55).

        It is generally accepted that when pavement is being constructed in the field, a paver screed would apply a certain preliminary compaction effort to the pavement before rollers are used to apply further compaction. This initial compaction effort is simulated by the compaction effort applied by the SGC during the first 8 gyrations (until $N_{initial}$). Contractors are required to reduce the air voids further using rollers until the pavement has reached approximately 92% G_{mm} or 8% air voids. At this point, the road is opened to traffic. Traffic causes densification of the pavement over its service life until the pavement reaches 98% G_{mm} or 2% air voids, which is considered the terminal density. At this point, the pavement could be prone to rapid accumulation of rutting.

        The study proposes that the compaction curve produced by the SGC be divided at 92% G_{mm}. The compactions that occur in the SGC between N_{init} and 92% G_{mm} and 92%

G_{mm} and 98% G_{mm} are considered to be representations of the construction compaction and traffic densification, respectively. The research group introduced two energy indices, the compaction energy index (CEI) and the traffic densification index (TEI). The CEI correlates with the construction side of the curve (N_{init} to 92% G_{mm}), and the TEI correlates with the traffic side of the curve (92 to 98% G_{mm}). The indices are found by integrating the area under the curve between any two points (i.e. 92%G_{mm} through 98% G_{mm}). The area is thought to represent the energy required for the gyratory to reduce the air voids of the mixture between those two points. Figure 2.2 illustrates the two areas under consideration.
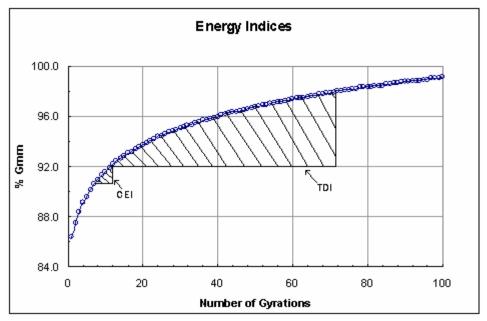
Figure 2.2 Energy Indices as proposed by Bahia et al. (55).
Mixes with higher CEI values are expected to require a great deal of energy to densify during construction. Although not all experts agree (71) , generally lower CEI values are therefore desirable because fewer roller passes will be required. Once traffic is on the pavement, it is desirable for the pavement to require a lot of energy (high traffic volume) to

densify. High TEI values are therefore desirable. The ideal pavement would be easy to densify during construction (low CEI) and hard to compact under traffic (high TEI).

Although the densification of the mixture is an important measure of performance, the resistance to distortion is also considered important and possibly more relevant to rutting under traffic. Since the CEI and TEI are derived from densification (volume change) only, they could be considered incomplete in representing the resistance of mixtures to distortion under traffic. Another measure is required that could measure directly the shear resistance of mixtures. This was measured using the Gyratory Load Plate Assembly (GLPA), which was developed by the same asphalt group in an effort to measure the resistance of the mixture to distortion (11) . The GLPA is placed in the gyratory compactor mold and provides a load measure that is recorded simultaneously with deflection. The vertical load and the eccentricity of that load are measured using 3 load cells placed at the edge of the plate. The measurements are used to calculate the resistive effort (w) as a function of the number of gyrations.

2.3.2 Resistive Effort (w)

In this research, the GLPA is used to determine the resistive effort of the mixes. This method for analyzing resistive effort data using a technique similar to the energy indices proposed by Bahia et al. (55) for use on the compaction data was first introduced and used by Delage (72) . The resistive effort curve is divided at 92% G_{mm} into a construction side and a traffic side. Under 92% G_{mm}, it is desirable for the mix to have a low resistive effort as it will enable ease of compaction by the contractor. Above 92% G_{mm}, it is desirable for the resistive effort of the mix to be high. The high level of resistive effort is an indicator of high

resistance of mixture to distortion under traffic, which will reduce rutting. To quantify the

resistive efforts above and below 92% G_{mm}, the area under the resistive effort curve between

N_{init} and 92% G_{mm} is calculated and termed the compaction force index (CFI), and the area

between 92% and 98% G_{mm} is calculated and termed the traffic force index (TFI). It is also

suggested that the construction energy index (CEI) relating to the compaction curve be

renamed the construction densification index (TEI). In this way, the values of the TEI and

TEI will relate to the densification curve, and the values of the CFI and TFI will relate to the

resistive effort curve. Figure 2.3 illustrates the four energy indices used as response variables

in this research.
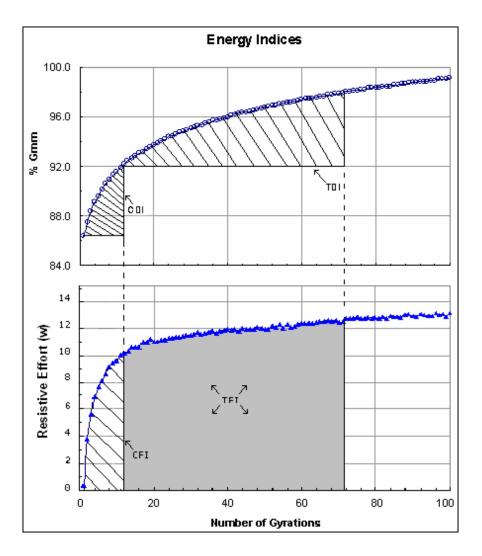
Figure 2.3: Response Variables: Energy Indices CEI and TEI; CFI and TFI.

2.3.3 Volumetric Data

Superpave volumetric mix design sets certain target air void levels for HMA at different compaction levels. At N_{init}, the % G_{mm} is supposed to be equal to or lower than 89%. This is meant to insure that the mix is not failing rapidly at the beginning of compaction. At N_{des}, the % G_{mm} is expected to be at 96%. All superpave mixes are designed primarily to meet this 4% air voids criteria. At N_{max}, the % G_{mm} is supposed to be less than

98%. For the purpose of this research, the $\%G_{mm}$ at N_{init}, $\%G_{mm}$ at N_{des}, and $\%G_{mm}$ at N_{max} are considered as response variables and used in the analysis.

Superpave also sets minimum limits on the voids in the mineral aggregate (VMA) allowed for mixes compacted to N_{des}. The limit is based on the nominal maximum aggregate size used in the mix. VMA is another response variable studied in this research.

In summary the control variables in this research are aggregate source, aggregate gradation, and fine aggregate angularity. The purpose of this research is to determine how FAA affects the mixture densification performance characteristics of different aggregate blends and sources. The response variables chosen to characterize the performance characteristics are CEI, CFI, TEI, TFI, $\%G_{mm}$ @ N_{init}, $\%G_{mm}$ @ N_{des}, $\%G_{mm}$ @ N_{max}, VMA.

CHAPTER THREE

EXPERIMENTAL METHODS AND RESULTS

3.1   Preparation of the Aggregate Blends

Four aggregate sources were selected for this research from different locations in the state of Wisconsin. These sources are used by four active asphalt contractors in the state. Each of the asphalt contractors provided two mix designs: one that represents a fine blend and one that represents an S-shaped blend. Using designs currently placed on highways in Wisconsin makes the results obtained from this research more relevant than if the designs had been created exclusively for this research. Appendix B contains all mix designs used in this research.

The mix designs were altered in such a way as to obtain four different blends from each original design. This was accomplished by first summing the proportions of manufactured and natural sands in the original mix design. This number represents the total percentage of fine aggregates in the original mix design. The only alterations made to the original designs involved changing the proportion of manufactured to natural sands, while keeping the total percentage of fine aggregates in the mix constant. Four blends were then created: one that contained only manufactured sand (100%), one that had 60% manufactured sand and 40% natural sand, one that contained 40% manufactured sand and 60% natural sand, and one that contained only natural sand (100%).

3.2   Fine Aggregate Angularity Determination

The fine aggregates used in each blend created for this research were individually

tested to determine their angularity. Literature regarding the FAA test suggests that it is not

appropriate to test for two FAA values and mathematically deduce the FAA value of

combinations of the original sands. Each combination of manufactured and natural sand used

in this research was therefore tested individually using method A of the FAA test procedure.

3.3   Mixture Testing

As discussed previously, eight response variables were selected for this research. The

response variables CDI, CFI, % G_{mm} @ N_{init}, % G_{mm} @ N_{des}, and VMA were calculated from

specimens compacted to N_{des} (100 gyrations).   The response variables TDI, TFI, and % G_{mm}

@ N_{max}, however, cannot be determined from compactions made to N_{des}. It was therefore

decided that it was necessary to compact to a number of gyrations that would guarantee that

all of those response variables could be determined. This meant that the samples should be

compacted to no less than 300 gyrations and to no less than 98% G_{mm}. For this reason, the

decision was made to compact specimens to 600 gyrations.

3.4   Specific Gravity Determination

Calculating the response variables requires accurate determination of maximum

specific gravity (G_{mm}) test values and bulk specific gravity (G_{mb}) test values. For this reason,

two G_{mm} (rice) specimens were tested at each FAA level for each blend (for a total of 8 Gmm

measurements per blend). Calculations based on G_{mb} values obtained from specimens

compacted to 100 gyrations are considered very accurate because there is no extrapolation

necessary to determine the G_{mb} at N_{des}. Calculations based on G_{mb} values obtained from 600 gyration specimens are not as accurate, however, because at 600 gyrations many samples have begun to "bleed" asphalt out of the specimen, and some aggregate crushing may have occurred. It was therefore necessary to use the average Gmb value of the two 100 gyration samples for analysis of the 600 gyration samples.

3.5   Duration of Research

For each combination of manufactured and natural sand, four sets of samples were compacted and two rices were run. For each set of compactions, two duplicate specimens were compacted to 100 gyrations and two were compacted to 600 gyrations. This leads to the fact that 128 compactions and 64 rices were necessary in this experiment. Figure 3.1 is an estimation of the time required for this research. Total time required was approximately 18 months. Testing was conducted by (1) Kenneth Delage, Graduate student, and research assistant, (2) Anthony Stakston, Graduate student and research assistant, (3) Andrew Braham, Graduate student and research assistant, and (4) Tom Snyder, University of Wisconsin junior student. All data analyses, calculations, and statistical analyses were performed by Kenneth Delage and Anthony Stakston. Expertise in statistical analysis was provided by Ms. Ssu-Wei Loh of the Asphalt Research Group and by Dr. Erik Nordheim and Dr. Wei-Yin Loh, professors at the University of Wisconsin in Madison. All the tasks were accomplished between October 1999 and March 2002.

Table 3.1: Time Required for Completing the Experimental Work of this Study.

Compaction	
Aggregate Prep.	1hrs
Batching and Mixing	1hrs
Aging	2hrs
Compaction	0.5hrs
G_{mb} Test	0.5hrs
Analysis	2.5hrs
Number of Compactions	216
Compaction Time	1620
G_{mm} Tests	
Aggregate Prep.	1hrs
Batching and Mixing	1hrs
Aging	2hrs
G_{mm} Test	0.5hrs
Number of G_{mm} Tests	108
G_{mm} Time	486hrs
Analysis and Concept Development Time	250hrs
Total Time	2356hrs
Learning Curve Correction Factor	1.3
Adjusted Total Hours	3063hrs
Days (assume 8 hrs/day)	382.9days

CHAPTER FOUR

DATA AND ANALYSIS

A complete summary of all the results for each response variable is listed in Appendix C. Graphical trends for each source are presented in Appendices D through G. The following sections provide a summary and a critical analysis of the results.

4.1 Graphical Trends

Based upon the data discussed in the literature review, it was expected that mixes with higher FAA values would have more resistance to densification and distortion than those with lower FAA values. With respect to this research, that suggests that CEI, CFI, TEI, and TFI values will all increase as FAA increases. This increased resistance would also entails that for a given compaction effort (number of gyrations), blends with a higher FAA value will be less dense (have a lower % Gmm) than blends with a lower FAA value.

4.1.1 Typical Trends for Effect of Changing FAA

Figure 4.1 shows a clear trend for the fine blend from source X. As the FAA of the fine aggregate increases from 40.1 to 47.8, the CEI increases more than five times and the CFI more than four times. Based on this result, it appears that mixes with higher FAA values would be more difficult to compact because they require more energy (CEI) and provide more frictional resistance (CFI). This significant impact of the angularity is not favorable, and, unless it is balanced by a similar improvement of resistance to traffic, there is a need for

optimization of the acceptance limit of the FAA value such that the mixtures are not too difficult to compact.

Figure 4.1: Trend of CEI and CFI for Source X, Fine Blend.

Figure 4.2 shows the information for the traffic related indices for the same blend which indicates that the TEI and TFI increase as the FAA increases. This indicates that mixes made with higher FAA are more resistant to densification and distortion (TEI) and provide more frictional resistance (TFI) than mixes with lower FAA values. This increase in the TEI is approximately three times while the increase in the TFI is approximately 3.25 times for the change of FAA from 40.1 to 47.8. It appears that for this blend, the resistance to traffic effects could offset the increase in resistance to compaction.

Figure 4.2: Trend of TEI and TFI for Source X, Fine Blend.

In terms of void content, as measured by %G_{mm} Figure 4.3 shows the %G_{mm} @ N_{init},

% G_{mm} @ N_{des}, and % G_{mm} @ N_{max}, which are the three measures used in the Superpave

volumetric system. The results confirm the expectation that voids are higher for higher FAA

values. The voids content increased by 4% for N_{init} while this increase was 3% for N_{des} and

2.5% for N_{max}, when the FAA values increased from 40.1 to 47.8.
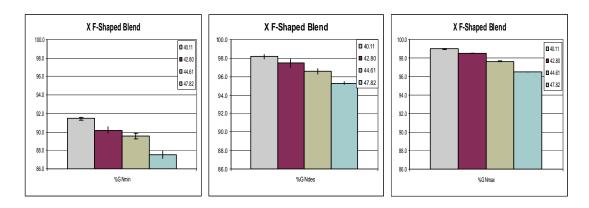
Figure 4.3: Trend of %G_{mm} @ N_{init}, N_{des}, and N_{max} for Source X, Fine Blend.

Figure 4.4 shows the effect of FAA on VMA at Ndes for the same blend. As shown,

the results also confirm the expectation that VMA values are higher for higher FAA values.

The VMA increased from 13.9 to 14.9 for this blend when FAA values increased from 40.1

to 47.8..

Figure 4.4: Trend of VMA for Source X, Fine Blend.

4.1.2 Typical Trends For Effects of Changing Asphalt Content

Based upon the data discussed in the literature review, it was expected that mixes with optimum - 0.5% asphalt content would have more resistance to densification and distortion, and optimum + 0.5% would have less resistance than mixes compacted at optimum asphalt content. In terms of this research, that would suggest that CEI, CFI, TEI, and TFI would all increase when asphalt content is decreased by 0.5% and decrease when asphalt content is increased by 0.5%. It was also expected that for a given compaction effort (number of gyrations), blends with optimum – 0.5% asphalt content will be less dense (have a lower % Gmm), and blends with optimum + 0.5% asphalt content will be more dense (have a higher % Gmm). The following is a brief discussion of some graphical trends observed from the data.

Figure 4.5 shows a clear trend for the F-Shaped blend from source X. As the asphalt content changes from optimum – 0.5% (5.3%) to optimum and then optimum + 0.5% (6.3%), the CEI decreases more than two times for both FAA values, and the CFI decreases more than half for both FAA values. Based on Figure 4.5, it appears that mixes with optimum –

0.5% asphalt content (5.3%) would be more difficult to compact. Since this effect of changing the asphalt content appears to be dependent on the FAA value, a significant interaction between FAA and asphalt content is expected.
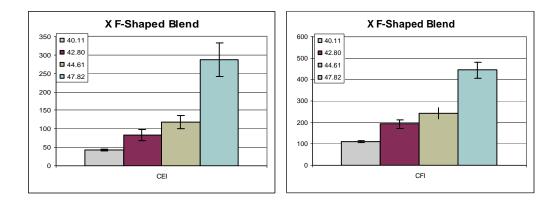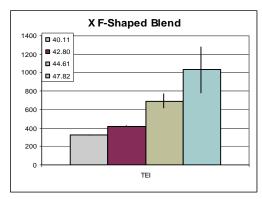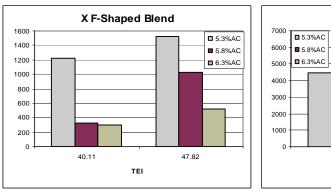

Figure 4.5: Trend of CEI and CFI for Source X, Fine Blend.

Figure 4.6 shows the information for the traffic related indices for the same blend of source X, the TEI and TFI decrease as the asphalt content increases from optimum – 0.5% (5.3%) to optimum + 0.5% (6.3%). This indicates that mixes made with higher asphalt content could be significantly less resistant to traffic densification and distortion than mixes with higher asphalt content values. This decrease in the TEI is approximately 75% for the FAA value of 40.11, and 65% for the FAA value of 47.82. While the decrease in the TFI is more than 75% for the same FAA value (40.11), and more than 65% for the other FAA value (47.82), it appears that for this mixture, the resistance to traffic is affected more by the asphalt content than the resistance to compaction during construction. It is also clear that the effects of changing asphalt content interact with the effects of changing the FAA values since the change in TEI and TFI are not the same for the two FAA values.
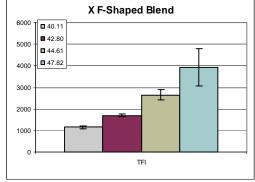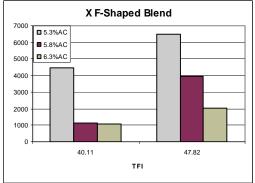
Figure 4.6: Trend of TEI and TFI for Source X, Fine Blend.

In terms of void content, as measured by %G_{mm}, Figure 4.7 shows the %G_{mm} @ N_{init}, % G_{mm} @ N_{des}, and % G_{mm} @ N_{max}, which are the three measures used in the Superpave volumetric system. The results confirm the expectation that %G_{mm} are higher for higher asphalt contents. The voids content increased by approximately 2% for both FAA values at N_{init} and N_{des} while the increase was 3% for both FAA values at N_{max}.

Figure 4.7: Trend of %G_{mm} @ N_{init}, N_{des}, and N_{max} for Source X, Fine Blend.

Figure 4.8 shows the effect of FAA on VMA at N_{des} for the same blend of source X. As shown, the results overall confirm the expectation that VMA are higher for higher asphalt

content values. One discrepancy is noticed in the FAA value of 40.11 the VMA actually

decreases from 5.3% to 5.8%. This could be only explained by a unique interactive effect.
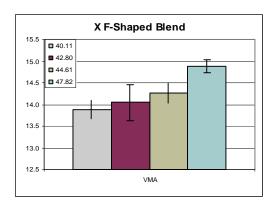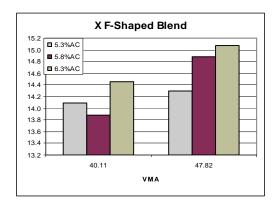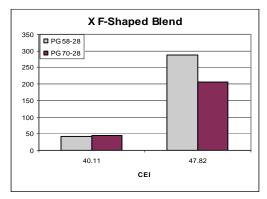

Figure 4.8: Trend of VMA for Source X, Fine Blend.

4.1.3   Typical Trends For Effects of Changing Performance Grade Asphalt

Based upon the data discussed in the literature review, it was expected that mixes with a

higher performance graded asphalt would have more resistance to densification and traffic

distortion. In terms of this research, that would suggest that CEI, CFI, TEI, and TFI would

all increase from a PG 58-28 binder to a PG 70-28 binder. This increased resistance to

compaction leads to an expectation that for a given compaction effort (number of gyrations),

blends with a PG 70-28 binder will be less dense (have a lower % Gmm), and blends with

PG 58-28 binder will be more dense (have a higher % Gmm).

Figure 4.9 does not show a clear trend for the F-Shaped blend from source X. Based

on results shown, it appears that for mixes with FAA value of 40.11 would be slightly more

difficult to compact using the PG 70-28, and mixes with FAA values of 47.82 would actually

be easier to compact using a PG 70-28 binder. This impact of performance grading is overall

favorable for construction, but unless it is balanced by an improvement in resistance to traffic, the impact is negligible.
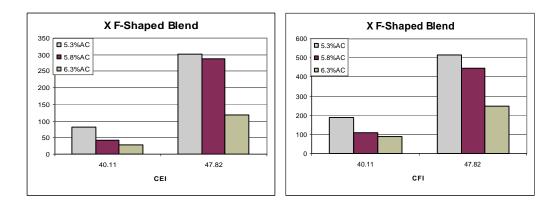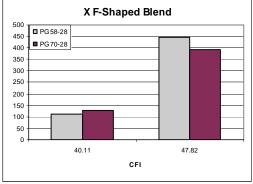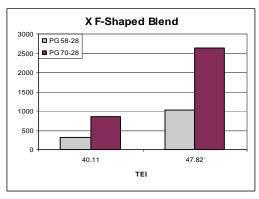

Figure 4.9: Trend of CEI and CFI for Source X, Fine Blend.

Figure 4.10 shows the information for the traffic related indices for the same blend of source X. The TEI and TFI increase as the performance grading increases from a PG 58-28 to a PG 70-28. This indicates that mixes made with higher performance grading asphalts could in effect have significantly more resistant to densification and distortion under traffic loading. The increase due to using the higher grade in the TEI is approximately 100% for the FAA value of 40.11, and 150% for the FAA value of 47.82. While the increase in the TFI is more than 100% for the same FAA value (40.11), and less than 100% for the other FAA value (47.82), it appears that for this mixture, the resistance to traffic effects is affected significantly by the performance grade of the asphalts. It is also clear that there is significant interaction between asphalt effects and FAA effects.
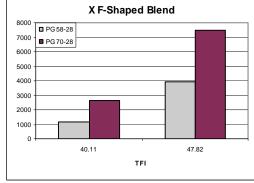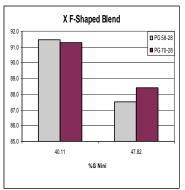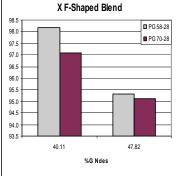
Figure 4.10: Trend of TEI and TFI for Source X, Fine Blend.

In terms of void content, as measured by %G_{mm} Figure 4.11 shows the %G_{mm} @ N_{init}, % G_{mm} @ N_{des}, and % G_{mm} @ N_{max}, which are the three measures used in the Superpave volumetric system. The results overall confirm the expectation that voids are lower for higher performance graded asphalts. The only exception is the FAA value of 47.82 at N_{ini}, this could be caused by initial packing of the mix into the mold before compaction since the construction indices are the most sensitive. The voids content decreased by approximately 0.2% for the FAA value of 40.11 at N_{ini} and increased by 1.0% for the FAA value of 47.82 at N_{ini}. While the voids content decreased by 0.9% and 0.2% for the FAA values of 40.11 and 47.82 respectively at N_{des}. The voids content also decreased by 1.3% and 1.5% for the FAA values of 40.11 and 47.82 respectively at N_{max}.
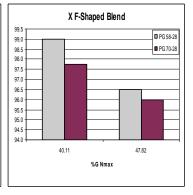
Figure 4.11: Trend of %G_{mm} @ N_{init}, N_{des}, and N_{max} for Source X, Fine Blend.

Figure 4.12 shows the effect of FAA on VMA at N_{des} for the same blend of source X. As shown, the results overall confirm the expectation that 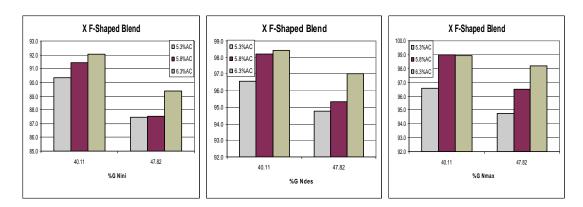VMA are higher for higher performance graded asphalts. The VMA increased from 13.9 to 14.9 for the FAA value of 40.11 and from 14.9 to 15.4 for the FAA value of 47.82..
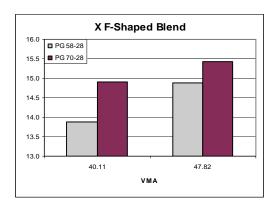
Figure 4.12: Trend of VMA for Source X, Fine Blend.

4.2   Statistical Analysis of Data

Because of the relatively large number of combinations of controlled factors, and because of apparent interactions, it is best to use statistical analysis to define trends and quantify affects of the major factors on the response variables.

4.2.1   Introduction to Analysis

"Analysis of Variance (ANOVA) models are versatile statistical tools for studying the relation between a dependent variable and one or more independent variables" (56). Each

independent variable is assigned a p-value within the ANOVA. The p-value is an indication

of how much evidence there is provided by the data that the independent variable affects the

dependent variable. According to Nordheim and Clayton (57), the statistical meaning of p-

values can be described in the following way:

(1) p-value < 0.001 = very strong evidence,

(2) (2) 0.001<p-value<0.01 = strong evidence,

(3) (3) 0.01 < p-value < 0.05 = moderate evidence, and

(4) 0.05 < p-value < 0.10 = weak evidence.

Based upon prior studies in this area, 0.05 was selected for this research. This assures that

the results will provide moderate evidence or better for each ANOVA. ANOVA models were

run on each dependent variable in this research using the SAS program. The ANOVA also

yields a coefficient of multiple determination, R^2. R^2 values range between zero and one,

with low values indicating that the model does not accurately describe the response variables.

The control variables used in this research are aggregate source (W, X, Y, Z),

aggregate gradation (Fine and S-Shaped), asphalt content (Optimum, Optimum –0.5%, and

Optimum +0.5%), Performance Graded Asphalt (58-28, 70-28) and FAA values (continuous

variable). These five control variables are termed main effects, and the interactions between

them are termed interactive effects. There are 10 possible interactive effects for the five

control values. The three way interactions were not included in this research because it is

typically difficult to interpret.

Table 4.1 shows two ANOVA Tables. The top part of the table is termed the full

model because it models both the significant main effects and interactive effects. The bottom

part of the table models only the main effects and is termed the main effects model.

Table 4.1: Example of ANOVA for Construction Force Index (CFI).

Analysis of Variance: Full Model					
Source of Variation	d.f.	Sum of Square	Mean Square	F-Ratio	Sig. Level
MAIN EFFECTS					
Source (S)	3	538461.9	179487.3	8.66	0.0002
AC (A)	2	626097.0	313048.5	15.1	<.0001
FAA (F)	1	249429.7	249429.7	12.03	0.0013
INTERACTIONS					
Source*AC (SA)	4	471397.9	117849.5	5.68	0.0011
FAA*Source (FS)	3	529183.0	176394.3	8.51	0.0002
					0.7637
Analysis of Variance: Main Effects Model					
MAIN EFFECTS					
Source (4 levels)	3	805743.4	268581.1	6.72	0.0008
Gradation (2 levels / source)	1	11637.5	11637.5	0.29	0.5922
PGGrade (2 levels / source)	1	77285.2	77285.2	1.93	0.1715
AC (3 levels / source)	2	662958.9	331479.5	8.29	0.0009
FAA (4 levels / source)	1	285186.0	285186.0	7.14	0.0106
					0.4846

Notice that in Table 4.1 the R^2 value for the full model (76.37%) is significantly higher than the R^2 value for the reduced model (48.46%). This indicates that the interactions between the main effects are very important. Notice also that the control variable gradation, and PG grade are not very significant in the main model as indicated by their p-values of 0.5922, and 0.1715 respectively (recall that acceptable p-values are below 0.05).   It is, however, also apparent that the model with only main effects has a very low R^2 value of 0.48, which is not acceptable. It is important to recognize that in the full model the interactive effects of source*asphalt content and FAA*source were the only interactive effects, among 10 possible interactions found to be relatively significant.

4.2.2 Correlation of Main Effects

When choosing control variables in an experiment, it is important to choose variables that are not highly correlated to each other. Choosing highly correlated control variables will cause errors in the ANOVA analysis. To determine if the control variables were correlated for this research, a correlation matrix was run using the SAS program. The output is displayed in Figure 4.13. Highlighted are the values of concern, the coefficients within the correlation matrix. These values are coefficients of determination, thus low values (those not close to 1.0) indicate that the variables are not well correlated. The correlation values range between -0.13752, and 0.13999, which indicates that the control variables are not well correlated. They are therefore appropriate to use as main independent effects in the ANOVA analysis.

```
The SAS System                        12:12 Saturday, November 10, 2001 213
The CORR Procedure
   5  Variables:     Source    Gradation PGGrade    AC        FAA
                             Simple Statistics
Variable          N        Mean      Std Dev        Sum      Minimum     Maximum
Source           52     2.34615      1.08256    122.00000    1.00000     4.00000
Gradation        52     1.30769      0.46604     68.00000    1.00000     2.00000
PGGrade          52     1.23077      0.42544     64.00000    1.00000     2.00000
AC               52     2.00000      0.48507    104.00000    1.00000     3.00000
FAA              52    44.15212      2.33166         2296    40.11000    47.82000
                   Pearson Correlation Coefficients, N = 52
                       Prob > |r| under H0: Rho=0
                 Source      Gradation      PGGrade           AC           FAA
Source          1.00000      -0.13752      0.07860      0.00000      0.13999
                              0.3310        0.5797       1.0000        0.3222

Gradation      -0.13752       1.00000      0.03043      0.00000     -0.00963
                0.3310                      0.8304       1.0000        0.9460

PGGrade         0.07860       0.03043      1.00000      0.00000     -0.04122
                0.5797        0.8304                     1.0000        0.7717

AC              0.00000       0.00000      0.00000      1.00000      0.00000
                1.0000        1.0000       1.0000                     1.0000

FAA             0.13999      -0.00963     -0.04122      0.00000      1.00000
                0.3222        0.9460       0.7717       1.0000
```

Figure 4.13 Correlation Matrix of Control Variables Source, Gradation, Asphalt Content,
Performance Graded Asphalt, and FAA

4.2.3   Number of trials

Upon completion of the testing phase of this research, a statistical analysis was

conducted to determine the number of trials (n), which should have been run in order to gain

statistically significant information about each response variable. This analysis was

conducted after the research was concluded because an understanding of the variance of the

data is necessary to determine an appropriate n value. Because the energy indices have not

been used previous to this research, little was known regarding their variance. The general

equation for computing n, provided by Dr. Erik Nordheim of the University of Wisconsin's

Statistical Department, is provided in Equation 4.1

$$n = 20 * (\sigma^2 / (\mu_2 - \mu_1)^2)$$

Equation 4.1

where: n = number of required tests
  σ^2 = sample variance
  $(\mu_2 - \mu_1)$ = difference in means

The difference in means $(\mu_2 - \mu_1)$ in Equation 4.1 is based upon an engineering

judgment pertaining to how large a difference between samples is considered practically

significant or important. For every level in this research, two repetitions were created. This

enabled a judgment to be made regarding the difference in means based on the difference

between each of the repetitions. For this research, the difference in means was determined for

each response variable to be twice the average difference between repetitions. Table 4.2 lists

the average difference between repetitions, σ^2, and the n resulting from the use of Equation

4.1 ($n_{required}$). Finally, the actual n used in this research is listed (n_{actual}). Note that in all

cases, the number of tests actually conducted exceeded the number required by the use of Equation 4.1.

Table 4.2 Number of Tests Required for Practically Meaningful Results.

Response Variable	Average difference between repetitions	σ^2	$n_{required}$	n_{actual}
CEI	243	50765	68	104
CFI	350	60263	65	104
TEI	1368	1614387	73	104
TFI	4290	18726449	53	104
% G_{mm} @ N_{init}	88.4	4	5	104
% G_{mm} @ N_{des}	96.1	3	3	104
% G_{mm} @ N_{max}	97.1	2	1	104
VMA	14.6	2	17	104

4.2.4   Interactions Between Independent Variables

Table 4.3 summarizes the R^2 values for models used for each response variable when the main effects are considered with their interactions and without their interactions. The analysis includes all sources tested in this project.

Table 4.3: R^2 Value for Models With and Without Interactions

Response Variable	R^2 Value of Model		Percent Difference [1]
	Main Effects and Interactive Effects	Main Effects Only	
%Gmm @ N_{init}	0.83	0.60	28%
%Gmm @ N_{des}	0.89	0.59	34%
%Gmm @ Nmax	0.82	0.51	37%
VMA	0.90	0.46	48%
CEI	0.82	0.44	46%
CFI	0.76	0.48	37%
TEI	0.79	0.42	46%
TFI	0.74	0.42	44%

---

[1] Decrease in R^2 value when interactive terms were removed from the model.

Table 4.3 shows that the R^2 values decrease significantly for models that exclude interactions from the analysis. The interactions between control variables are therefore very important to consider for all response variables and models that consider only the main effects are considered unreliable to predict these response variables. The importance of this finding is that limits used to control main effects without considering the other factors could be misleading. In other words, limits on the FAA values should be based on gradation, asphalt content, and possibly other factors.

4.2.5 Replicate Error

Every test conducted for this research was repeated twice. Because of this, each test has two duplicates, and therefore 'duplicate' can be considered a control variable. By running an ANOVA analysis on the response variables, with duplicate included as a control variable, it is possible to determine how much error is related to experimental error. Table 4.4 summarizes the R^2 values obtained by running ANOVA analysis with and without considering duplicate as a control variable.

Table 4.4: Effect of Replicates on Data.

Response Variable	R^2 Value of Models		Percent Difference	P value for Replicate
	Main Effects and Interactive Effects (w/o duplicates)	Main Effects and Interactive Effects (w/ duplicates)		
%Gmm @ N_{init}	0.835	0.864	-4%	0.5992
%Gmm @ N_{des}	0.893	0.891	0%	0.6591
%Gmm @ Nmax	0.820	0.845	-3%	0.8288
VMA	0.898	0.865	4%	0.5574
CEI	0.821	0.831	-1%	0.3467
CFI	0.764	0.837	-10%	0.4976
TEI	0.786	0.808	-3%	0.6792

| TFI | 0.741 | 0.763 | -3% | 0.6508 |

Table 4.4 shows that the R^2 value increased for every response variable when the factor duplicate was considered as a control variable. With the exception of CFI, none of these increases are very meaningful. This indicates that the testing procedure itself was not a large source of error in this experiment. It is believed that CFI is influenced highly by replicates because it is calculated from data beginning at the first gyration. During the first few gyrations, there is a lot of variability because of how the material may have initially been put in the compaction mold. Small variations in how the material is poured into the mold can have a large impact on data received during the first few gyrations of a compaction.

4.2.6   Sample Variance for Response Variables

Due to the GLPA being a relatively new testing procedure, there is no accepted sample variance for this data collected. Therefore it was necessary to calculate the sample variance from the data collected for this research. This was only possible since replicates were taken during the research. From the standard deviation between the replicates and the average of the replicates, the coefficient of variation (COV) for each replicate set was calculated. Then the COV for all sets was averaged to get a pooled sample variance. This pooled sample variance is the percentage difference that could be used to show statistically that two samples are different. The pooled sample variance for each response variable is shown in Table 4.5.

Table 4.5: Sample Variance of Response Variables

	CEI	CFI	TEI	TFI	%Gmm N_{init}	%Gmm N_{des}	%Gmm N_{max}	VMA
AVG	0.14	0.10	0.05	0.05	0.003	0.003	0.001	0.02

The construction indices show the largest sample variance of all eight response variables. This is believed to be due to how the material may have initially been put in the compaction mold. Small variations in how the material is poured into the mold can have a large impact on data received during the first few gyrations of a compaction.

The traffic indices show a smaller sample variance due to less variability in the later stages of compaction and the larger duration of the compaction. The sample variance for the TEI, and TFI is 0.05 for both indices.

The volumetric indices (%Gmm @ N_{init}, %Gmm @ N_{des}, and %Gmm @ N_{max}) had a significantly smaller pooled sample variance due to the high repeatability of this test method. This is shown by the sample variances of 0.003, 0.003, and 0.001 for the respective indices. The VMA's pooled sample variance was 0.02, which is significant since VMA is reported in tenths, therefore any difference reported is actually significant.

4.3   Summary

Table 4.6 is a summary of the significance level of the main and interacting effect on the response variables, as well as the R^2 for each model. This analysis was conducted with all four sources, two gradations, two performance graded asphalts, three asphalt content and four FAA values. Those Control Variables with p-values greater than 0.05 are not listed and were removed from the model.

Table 4.6 is divided into two main sections. The top section, titled "Full Analysis" was run including all control variables and interactions. The final section titled "Main Model" did not consider interactions. Within the table, the word "No" is used to indicate

factors which were not statistically significant. In this case, they were removed from the model, and the model was repeated. This procedure was repeated until all factors in the model were significant.

Table 4.6: Significance of Control Variables and Interactions in Affecting Response Variables

	Response Variable	Main Effects					Interactions					R^2	Se / Sy
		Source (S)	Gradation (G)	PG Grade (P)	AC (A)	FAA(F)	S*G	S*P	S*A	S*F	G*P		
Full Model	CEI	0.0001	0.0324	0.001	0.0002	0.0001	No	0.005	0.001	0.0001	0.025	0.82	0.22
	CFI	0.0002	No	No	<.0001	0.0013	No	No	0.001	0.0002	No	0.76	0.31
	TEI	0.0098	0.0283	<.0001	<.0001	0.2606	No	0.0001	No	<.0001	0.05	0.79	0.67
	TFI	0.013	No	0.0005	<.0001	0.7833	No	0.0011	No	<.0001	No	0.74	0.61
	%Gmm @ Ninit	0.0057	0.1162	No	0.0001	<.0001	0.001	No	0.0345	0.0045	No	0.83	0.20
	%Gmm @ Ndes	<.0001	0.0007	0.0597	<.0001	<.0001	No	0.002	<.0001	<.0001	No	0.89	0.12
	%Gmm @ Nmax	0.0006	0.0004	0.2537	<.0001	0.1304	0.0232	No	0.0121	0.0004	0.0251	0.82	0.22
	VMA	<.0001	<.0001	<.0001	<.0001	0.0139	<.0001	No	<.0001	<.0001	No	0.90	0.11
Main Model	CEI	0.0015	No	No	0.6329	0.072						0.44	1.27
	CFI	0.0008	No	No	0.5922	0.1715						0.48	1.06
	TEI	No	No	0.2966	0.2072	No						0.42	1.38
	TFI	No	0.1535	0.0858	0.0058	No						0.42	1.39
	%Gmm @ Ninit	0.0001	No	No	0.1111	0.909						0.60	0.67
	%Gmm @ Ndes	0.0113	0.017	No	0.326	<.0001						0.59	0.69
	%Gmm @ Nmax	No	0.07	No	0.0226	No						0.51	0.94
	VMA	No	0.0017	0.0087	0.0298	No						0.46	1.16

The statistical analysis results shown in Table 4.6 lead to the following findings:

1.   FAA appears to be highly significant in modeling of response variables related to the initial compaction stage. In the full model, FAA is significant for CEI, CFI, % G_{mm} @ N_{init} and % G_{mm} @ N_{des}, which represent the mixture performance in the early compaction stages. The FAA is not, however, as significant for the other response variables, which relate to later stages of densification and distortion. This indicates that increasing the FAA of a blend will cause noticeable

differences in the behavior of the mix during construction but could have minor effect during service under traffic.

2. Asphalt content appears to be highly significant in modeling of response variables related to both stages of construction and of traffic. In the full model, asphalt content is significant for all response variables. This indicates that changing the asphalt content of a blend will cause noticeable differences in the behavior of the mix during construction, and traffic.

3. All response variables were significantly affected by source in the full model. Although Source is less important than asphalt content, it appears to be significant in modeling all the response variables.

4. Source and gradation interaction effect is also significant but it affects only the volumetric properties. Source and FAA interaction effect is significant for all response variables whereas FAA and gradation interaction does not appear to be significant for any response variable.

5. The R^2 values for the full model are significantly higher than the R^2 values for the reduced model. This indicates that the interactions between the main effects are important. The analysis indicates that interactions between control variables are very important to consider for all response variables. Models that consider only the main effects are considered unreliable to explain the response variables.

4.4   Source By Source Analysis

The graphical and statistical analysis presented earlier in this report showed some very clear trends of FAA affects on the mixture response variables and of highly significant

interactive effects with source of aggregate. For this reason, it was decided to run statistical

analysis on each source individually to carefully quantify the effect of FAA. For each

source, the number of control variables reduced from five to four (since source could no

longer be considered as a control variable). All sources do not include the interaction of

gradation and asphalt content since the asphalt content was only changed with the fine

gradation. Source W was, however, different from the other three sources in that there is

only one gradation (fine) for source W. This limited the number of main effects to three

(asphalt content, performance graded asphalt, and FAA) for source W.

Table 4.7: Source by Source Analysis of Data.

Source W

	Response Variable	Main Effects			Interactions		R^2	Se / Sy
		PG Grade (P)	AC (A)	FAA(F)	P*F	A*F		
Full Model	CEI	No	No	0.0109	No	No	0.80	0.20
	CFI	No	0.0273	0.0029	No	No	0.86	0.16
	TEI	0.0059	0.0092	0.0672	0.0057	0.0088	1.00	0.00
	TFI	0.003	0.0038	0.0113	0.0029	0.0035	1.00	0.00
	%Gmm @ Ninit	No	0.0165	0.0002	No	No	0.93	0.07
	%Gmm @ Ndes	0.2068	0.0124	0.0192	0.1985	No	0.92	0.08
	%Gmm @ Nmax	0.013	0.0251	0.0112	0.0125	0.0233	1.00	0.00
	VMA	0.0091	0.0356	0.0013	No	No	0.93	0.08

Significance of Control Variables in Affecting Response Variables

Source X

	Response Variable	Main Effects				Interactions				R^2	Se / Sy
		Gradation (G)	PG Grade (P)	AC (A)	FAA(F)	G*P	G*F	P*F	A*F		
Full Model	CEI	No	No	No	<.0001	No	No	0.015	No	0.76	0.32
	CFI	0.0038	0.0417	0.0271	<.0001	No	0.0031	No	No	0.95	0.05
	TEI	0.1826	0.7352	No	0.0135	0.0034	No	No	No	0.96	0.05
	TFI	0.0163	0.0427	0.032	0.0753	0.0009	0.0077	No	0.0366	0.98	0.03
	%Gmm @ Ninit	0.0014	0.001	0.0711	<.0001	0.0307	No	No	No	0.95	0.05
	%Gmm @ Ndes	0.0027	0.0027	0.0029	0.0007	<.0001	0.0012	0.0018	0.0028	1.00	0.00
	%Gmm @ Nmax	0.0104	0.0148	0.0058	0.1134	0.0001	0.0062	0.0125	0.0064	0.99	0.01
	VMA	0.0009	0.0096	No	No	No	No	No	No	0.78	0.54

Significance of Control Variables in Affecting Response Variables

Table 4.7, Continued: Source by Source Analysis of Data.

Source Y

	Response Variable	Main Effects				Interactions			R^2	Se / Sy
		Gradation (G)	PG Grade (P)	AC (A)	FAA(F)	G*F	P*F	A*F		
Full Model	CEI	0.0001	<.0001	0.0005	0.0002	No	<.0001	0.0006	1.00	0.00
	CFI	<.0001	<.0001	<.0001	<.0001	No	<.0001	<.0001	1.00	0.00
	TEI	0.0164	0.0001	0.0002	<.0001	No	0.0002	0.0003	1.00	0.00
	TFI	0.0268	<.0001	<.0001	<.0001	0.0324	<.0001	<.0001	1.00	0.00
	%Gmm @ Ninit	<.0001	<.0001	<.0001	0.0041	No	<.0001	<.0001	1.00	0.00
	%Gmm @ Ndes	<.0001	0.0003	0.0055	0.0001	No	0.0004	0.0038	1.00	0.00
	%Gmm @ Nmax	0.0001	0.002	<.0001	0.0007	No	0.0031	No	0.99	0.01
	VMA	<.0001	0.002	0.0002	0.0026	No	0.0028	0.0005	1.00	0.00

Source Z

	Response Variable	Main Effects			Interactions			R^2	Se / Sy
		Gradation (G)	PG Grade (P)	FAA(F)	G*P	G*F	P*F		
Full Model	CEI	0.0066	0.0142	0.0004	0.0288	No	0.0121	0.93	0.07
	CFI	0.0211	0.0003	<.0001	0.0009	0.0152	0.0003	0.99	0.01
	TEI	No	0.0009	0.0002	No	No	0.0007	0.92	0.09
	TFI	No	0.0036	0.0012	No	No	0.0029	0.86	0.16
	%Gmm @ Ninit	<.0001	0.0007	<.0001	0.0016	No	0.0007	0.99	0.01
	%Gmm @ Ndes	0.8151	0.003	<.0001	0.028	No	0.0028	0.97	0.03
	%Gmm @ Nmax	No	0.0001	<.0001	No	No	0.0001	0.96	0.05
	VMA	0.0489	0.0052	<.0001	0.0013	0.0475	0.0042	0.98	0.02

4.5   Conclusions

The statistical analysis of the results presented in this chapter has shown the

following trends,

1.   Regarding the importance of the FAA on mixture performance, it is found that the

effect of FAA is highly dependent on aggregate source and that there is significant

interactions between FAA and Gradation, FAA and Asphalt Content, and FAA and

Performance Graded Asphalt on all response variables.

2.   Regarding the importance of the asphalt content on mixture performance, it is found that the effect of asphalt content is highly dependent on aggregate source and that there is a significant interaction between FAA and Asphalt Content.

3.   Regarding the importance of the performance-graded asphalts on mixture performance, it is found that the effect of performance-graded asphalts is highly dependent on aggregate source, and that there is significant interactions between Gradation and Performance Graded Asphalt, and FAA and Performance Graded Asphalt.

The next chapter is a summary of the sensitivity analysis of the results to show the quantitative effects of changing FAA, asphalt content, and performance graded asphalts on the different response variables. The models shown in this chapter are used in the sensitivity analysis.

CHAPTER FIVE

SENSITIVITY ANALYSIS

5.1 Sensitivity Analysis Overview

This analysis is presented to determine how sensitive the response variables are to changes in FAA. The results can be used to determine the limits of FAA that should be used to establish a criterion in the specification. In conducting this analysis, a regression model was created for each of the response variables using the statistical program SAS. Due to the high importance of aggregate source on response variables, the models were source specific, and they include different combination of main effects depending on source. For sources W, and Z the factors include FAA, asphalt content, and performance graded asphalt. For sources X, and Y the models included gradation, FAA, asphalt content, and performance graded asphalt. Some of the first order interactions were also included. The source specific models for each source are shown in Equations 5.1, 5.2, 5.3, and 5.4.

Source W:

Response Variable = $K + C_2*(P) + C_3*(A) + C_4*(F) + C_9*(P*F) + C_{10}*(A*F)$

$$\text{Equation 5.1}$$

Source X

Response Variable = $K + C_1*(G) + C_2*(P) + C_3*(A) + C_4*(F) + C_5*(G*P) + C_7*(G*F) + C_9*(P*F) + C_{10}*(A*F)$

$$\text{Equation 5.2}$$

Source Y

Response Variable = $K + C_1*(G) + C_2*(P) + C_3*(A) + C_4*(F) + C_7*(G*F) + C_9*(P*F) + C_{10}*(A*F)$

$$\text{Equation 5.3}$$

Source Z

Response Variable = $K + C_1*(G) + C_2*(P) + C_4*(F) + C_5*(G*P) + C_7*(G*F) + C_9*(P*F)$

$$\text{Equation 5.4}$$

Where K = constant, G = Gradation, P = Performance Graded Asphalt, A = Asphalt Content, F = FAA, and C_x = Coefficients

Linear regression was used to determine the value of each of the coefficients (K, C_1….C_6) for the general equation. Table 5.1 lists the coefficients obtained for each response variable.

The coefficients shown in Table 5.1 were derived from the statistical regression of each response variable with the following independent controlled variables. The following codes and levels were used in the regression analysis:

1.   Gradation (G): Fine Gradation = 1, S-Shaped Gradation = 2

2.   PG grade (P): PG 58-28 = 1, PG 70-28 = 2

3.   Asphalt Content (A): Optimum AC – 0.5% = 1, Optimum AC = 2, Optimum AC + 0.5% = 3

4.   Fine aggregate angularity (F): FAA is continuous

It can be observed that the R^2 values for all models are above 90% indicating that the models give a very good prediction of the response variables by using the values of the controlled variables. Since the models give such a high level of prediction power, they can be used to estimate the effect of each control variable on the mixture response. In models that include only main effects the coefficients would provide the sensitivity factor. In this context the sensitivity is defined as the amount of change in response (such as % Gmm at Ndesign) for one unit change in the controlled variable (such as FAA). However, since there are interactive factors in each model, the sensitivity analysis has to be done using selected changes in value for one controlled variable (such as FAA) while keeping the values for all other variables constant.

Table 5.1: Regression Model Coefficients

Source W

	Response Variable	Intercept	PG Grade (P)	AC (A)	FAA(F)	P*F	A*F	R² of model	Se / Sy
Full Model	CEI	-5720.1	-1203.0	1954.2	132.4	27.2	-44.9	0.94	0.06
	CFI	-5966.0	-1773.6	2151.6	141.7	39.9	-50.0	0.96	0.05
	TEI	26570.0	-14794.0	2680.2	-488.2	337.1	-91.5	0.86	0.17
	TFI	36070.0	-37524.0	19399.0	-489.7	850.1	-526.6	0.84	0.19
	%Gmm @ Ninit	135.8	16.8	-9.2	-1.1	-0.4	0.2	0.97	0.03
	%Gmm @ Ndes	118.0	18.4	-13.5	-0.5	-0.4	0.3	1.00	0.00
	%Gmm @ Nmax	101.0	22.0	-12.9	-0.1	-0.5	0.3	0.91	0.10
	VMA	4.1	-11.5	3.8	0.2	0.3	-0.1	0.86	0.16

Source X

	Response Variable	Intercept	Gradation (G)	PG Grade (P)	AC (A)	FAA(F)	G*P	G*F	P*F	A*F	R² of model	Se / Sy
Full Model	CEI	-2055.4	446.1	464.7	85.0	51.3	-35.0	-8.3	-11.2	-2.8	0.93	0.07
	CFI	-2735.7	917.8	348.6	11.6	71.5	-46.7	-20.5	-7.8	-1.5	0.96	0.04
	TEI	-4991.5	1590.5	2699.1	-278.5	65.5	-2177.4	28.7	10.6	-4.6	0.79	0.27
	TFI	-20909.0	12792.0	-1528.9	1019.1	539.3	-3148.7	-245.7	154.1	-67.9	0.91	0.10
	%Gmm @ Ninit	112.5	-7.8	-4.0	2.9	-0.5	1.5	0.1	0.1	-0.1	0.97	0.03
	%Gmm @ Ndes	119.3	-6.3	-6.4	0.1	-0.5	2.5	0.1	0.1	0.0	0.96	0.04
	%Gmm @ Nmax	116.2	-5.8	-5.4	-0.1	-0.4	2.3	0.1	0.0	0.0	0.90	0.11
	VMA	7.5	3.5	1.9	-0.9	0.1	-0.4	-0.1	0.0	0.0	0.93	0.07

Source Y

	Response Variable	Intercept	Gradation (G)	PG Grade (P)	AC (A)	FAA(F)	G*F	P*F	A*F	R² of model	Se / Sy
Full Model	CEI	-609.6	-2347.5	3795.8	-453.8	44.1	47.2	-83.0	1.2	0.89	0.13
	CFI	6071.5	-3708.7	3777.5	-2351.5	-100.0	77.4	-83.3	42.7	0.94	0.11
	TEI	50903.0	-18102.0	27020.0	-20848.0	-1136.6	394.3	-537.1	446.6	0.98	0.02
	TFI	263788.0	-98377.0	153368.0	-110309.0	-5786.0	2155.7	-3250.7	2382.6	0.95	0.05
	%Gmm @ Nini	124.2	36.8	-10.5	-25.7	-1.0	-0.8	0.2	0.7	0.86	0.16
	%Gmm @ Ndes	90.7	17.8	-19.7	0.2	0.0	-0.4	0.4	0.1	0.97	0.03
	%Gmm @ Nmax	88.6	11.1	-24.7	8.4	0.0	-0.2	0.5	-0.1	1.00	0.00
	VMA	31.2	-0.4	17.2	-16.3	-0.2	0.0	-0.4	0.3	0.96	0.05

Source Z

	Response Variable	Intercept	Gradation (G)	PG Grade (P)	FAA(F)	G*P	G*F	P*F	R² of model	Se / Sy
Full Model	CEI	10074.0	-3944.1	-7434.8	-219.4	424.8	82.7	162.0	0.97	0.03
	CFI	8039.2	-2852.7	-6616.6	-167.6	360.6	57.9	142.9	0.99	0.01
	TEI	21462.0	7480.3	-37136.0	-513.9	-419.7	-167.1	903.0	0.95	0.05
	TFI	60001.0	28127.0	-112201.0	-1424.6	-1723.5	-626.1	2728.5	0.92	0.09
	%Gmm @ Ninit	82.8	1.7	37.6	0.1	-2.2	0.0	-0.8	0.99	0.01
	%Gmm @ Ndes	81.7	5.7	26.3	0.3	-1.1	-0.1	-0.6	0.97	0.03
	%Gmm @ Nmax	74.0	3.4	30.3	0.5	-0.5	-0.1	-0.7	0.97	0.03
	VMA	5.2	7.8	-22.5	0.3	2.0	-0.3	0.5	0.98	0.02

5.2 Correlation between Construction and Traffic Indices measured by the SGC

As indicated in the earlier sections, two types of measures were used in this study to monitor the densification of asphalt mixtures in the Superpave Gyratory Compactor. The volumetric properties, as measured by the change in density (% Gmm), were used to derive the CEI and the TEI. The Gyratory Load Plate Assembly (GLPA) was used to measure the force distribution during compaction and to derive the CFI and the TFI. The GLPA is a newly developed device that requires special hardware and software to be attached to the gyratory. The GLPA is also not available commercially for all types of gyratory equipment used by contractors in the field, which makes it difficult to be used on routine basis.

During the graphical and statistical analysis, a trend was seen between the two construction (CEI and CFI) and traffic indices (TEI and TFI). It appeared that the two construction and traffic indices correlated in their trends. Therefore it was decided to see if they were correlated since if the indices were highly correlated there would be redundancy in the analysis and lab work. The redundancy would be because the gyratory load cell plate assembly (GLPA) and the Superpave gyratory compactor (SGC) give the same information but in two different methods.

This section includes analysis to test the hypothesis that the energy indices (CEI and TEI) are highly correlated and thus can be used to define same performance as the force indices (CFI and TFI).

5.2.1 Construction Indices Correlation

The correlation between CEI and CFI is shown in Figure 5.1 for all combinations of sources, gradations and asphalt grades. A linear equation and a second order polynomial were used to fit the data. It can be seen that both equations show a relatively good fit as

evident by the high values of the R^2 calculated (R^2 = 0.854 for the linear regression and

0.938 for the polynomial). It is also shown that out of the 50 mixtures only 4 show very high

values of CEI and CFI. To ensure that these mixtures are not resulting in a misleading

goodness of fit, they were removed and the correlations were recalculated as shown in Figure

5.2.

The results shown in Figure 5. 2 indicate that the goodness of fit remains high but that

a polynomial (non-linear) equation offers a much better fit for the data. In both cases it is

clear that there is a unique relationship between these 2 parameters
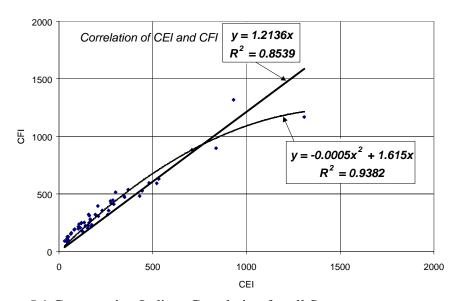
Figure 5.1 Construction Indices Correlation for all Sources

To further understand the relationship and examine the uniqueness of this

relationship, the data for each source was fitted separately. Table 5.1 lists the values of R^2

calculated for each of the sources when a linear regression model was used. The R^2 values

for the correlation of the construction indices for the fine and S-shaped blend for each source

vary between a low of are 0.948 and a high value of 0.992. Although the correlations for individual mixtures are better than the overall general correlation, it would be unrealistic to recommend using a mixture- specific correlation. The correlations however indicate that there is a minor effect of mixture aggregate source and gradation, which will be considered as part of the uncertainty in the relationship of VEI and CFI.
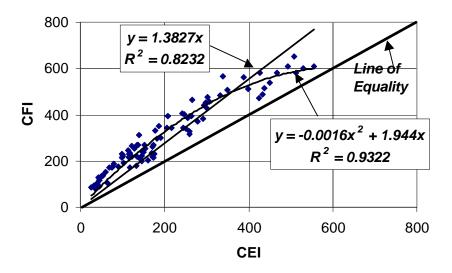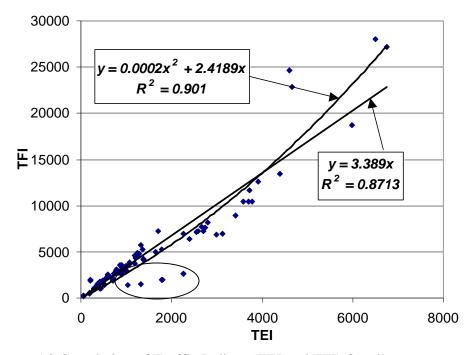
Figure 5.2 Construction Indices Correlation for a reduced set of mixtures.

Table 5.1: R^2 of the Linear Correlation between the Construction Indices (CEI and CFI) For Various sources

Source	Gradation	R^2
W	Fine	0.9912
X	Fine	0.9792
	S-Shaped	0.9594
Y	Fine	0.9481
	S-Shaped	0.9868
Z	Fine	0.9488
	S-Shaped	0.9888

5.2.2 Traffic Indices Correlation

     Similar type of correlation analysis was conducted for the TEI and the TFI. Figure 5.3 clearly shows the correlation of these traffic indices for all mixtures.

Figures 5.3 Correlation of Traffic Indices (TEI and TFI) for all sources.

     A simple linear fit shows a value of R^2 of 0.87 while a curvilinear fit (second order polynomial) shows a slightly higher R^2 value of 0.90. There are several data points that appear to be outside of the general trends, such as the 4 mixtures with very high TFI values (more than 20000) and there is a set of data showing a unique relationship of lower TFI for the same range of TEI. IN order to understand these outliers, a search was conducted to see if the set of data assumed to be outliers belong to some specific mixtures. It was found the unique set with very low TFI (marked with a oval in Figure 5.3 belongs to Source X with S-shaped gradation.
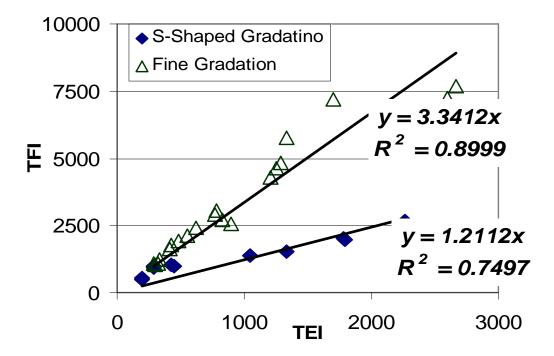
Figure 5.4 Correlations of TEI and TFI for Mixtures with Source X only .

This set had a very low TFI values and in fact lost some of the asphalt as the mixture
collapsed and reached 100% Gmm. Figure 5.4 depicts the significant difference in
correlations between the fine graded mixtures, which follows the general trend observed fro
the mixtures made with other sources and gradations, and the S-shaped graded mixtures.
Since these mixtures shoed very low air voids and very low TFI, they could be assumed as
outliers. The data points representing these mixtures were taken out of the data set. In
addition, the data points with very high TFI values were also taken out and the correlations
were re-calculated as shown in Figure 5.5.
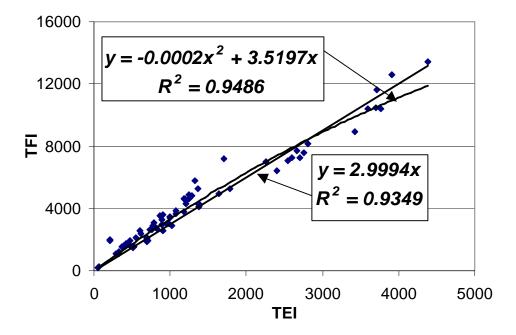
Figure 5.5 Correlations of TEI and TFI Values for a Reduced Set of Data

As depicted in the figure the R^2 values for the linear and the curvilinear fit are both higher than 0.93 which clearly indicates that there is a significant correlation between these two measures. In this case the linear fit could be used which shows that the TFI is estimated at 3.0times the TEI value calculated from the densification curve of the gyratory compactor.

In summary, it appears that the energy indices (CEI and TEI) estimated from the densification curves measured with the Superpave Gyratory Compactor are very good indicators of the frictional resistance of a mixture estimated from measuring the force distribution on a mixture (CFI and TFI). There is some uncertainty in the relationships as the correlations are not perfect, but for the sake of simplicity, it appears that using the densification curves (CEI and TEI), without measuring the force distributions, and without using a load plate assembly, could give very good predictions. It is therefore recommended that the initial mixture acceptance criteria be based on densification curves. In the next

sections the sensitivity of the energy and the force indices will be evaluated by using the

models developed in the previous section. Because of the high correlations found between

CEI and CFI, and between TEI and TFI, the discussion will be limited to the CEI and TEI.

5.3 Sensitivity Analysis of Mixture Responses to Fine Aggregate Angularity and Asphalt Content Changes

To determine how sensitive the response variables are to changes in FAA, Equation

5.1, 5.2, 5.3, and 5.4 were used to calculate the change in the response variables listed in

Table 5.1 for one unit change in the FAA value relative to the response variables measured at

an FAA value=44. The value of 44 was selected as a mid value within the range measured

fro the fine aggregates used in this study (40 to 48). It was also chosen because it is within

the Superpave requirements for HMA used on highways designed for different design ESALs

(refer to Table 1.1). Because of the relatively high interactive effects, the models were used

for each combination of source, gradation, asphalt content, performance graded asphalt

(three levels of asphalt content, two levels of gradation, and two levels of performance

graded asphalt). Instead of looking at the overall average effect, the individual effects were

calculated for the different combinations. Appendix I lists the results of this analysis. The

following sections include a summary of these changes for each or for sets of the response

variables.

5.2.1 Changes in volumetric properties:

Table 5.3 is prepared to show the changes in the volumetric properties of mixtures as

used in the Superpave mixture design as a result of changing the FAA value (angularity).

These properties include % Gmm at Ninitial, % Gmm at Ndesign, % Gmm at Nmax, and VMA at Ndesign. The following observations could be made:

- Density at Ninitial decreased with increasing FAA value for all 34 combinations with only 2 exceptions for source Y, fine gradation, at the asphalt content of 0.5 above optimum. The decrease in density, however, vary significantly depending on the type of mixture between a maximum of 1.7 % and a minimum of only 0.2 % Gmm. For 10 combinations the decrease in density is more than 1.0% Gmm for every one unit increase in FAA value and for 12 other combinations it is more than 0.4 %, which is more than the sample variance estimated at 0.2 %Gmm . These results indicate that if the FAA requirement is increased from 40 to 45, the decrease in % Gmm at Nini could be as high as 5 % Gmm for many types of mixtures, which is very significant and could require a significant increase in compaction effort.

- Density at Ndesign is also changing significantly as a result of changes in FAA. In 24 of the mixtures a decrease in density in the range of 0.1 to 1.1 % Gmm per unit change in FAA was estimated. The decrease in density could be as high as 5.5% Gmm when the FAA is changed from 40 to 45, which is very significant and could result either in more compaction effort required to achieve density in the field or in significant increase in asphalt content to achieve density. In the remaining 10 mixtures an increase in density resulted form increasing the FAA value. The increase in density, which ranged between 0.1 and 0.6 % Gmm per unit change in FAA, indicates that increasing FAA does not always result in more resistance to densification or distortion under conditions simulating traffic. It is also seen that there is a strong dependency on aggregate source and asphalt content.

- Density values at Nmax follow a similar trend to the values at Ndesign. The density

  decreased in 22 of the mixtures while they increased for the other 12 mixtures. The

  decreased ranged from 0.1 % Gmm to 1.0 % Gmm while the increase ranged between

  0.1 % and 0.8 % Gmm per unit change in FAA. The estimated increases in % Gmm

  at Nmax are not considered favorable and could be indicators of mixture instability

  under traffic loading.

- The VMA values also change as a result of the changes in FAA. The changes range

  between a reduction of 0.7% and an increase of 1.0 % per unit change in FAA.

In summary the results of the analysis clearly indicate that volumetric properties are

sensitive to FAA values. The trends however do not support the contention that there is one

well-established trend between increasing FAA values and changes in volumetric properties.

It is clear that there are interactive effects and for some mixtures asphalt contents will have to

be lowered to meet certain criteria.

5.2.2 Changes in Densification Characteristics

Table 5.4 is prepared to show the changes in the CEI and the TEI values,

which are two densification parameters derived from the measurements of the gyratory

compactor. The CEI is used as an indicator of mixture resistance to compaction during

construction to a density of 92 % Gmm. Higher values are not favorable because they

indicate more resistance and more compaction effort required. The TEI is a measure of

energy required to densify a mixture from 92 % Gmm to 98 % Gmm, which is expected to

occur under traffic movement in the field. Higher TEI values are favorable because they

indicate more resistance to densification under traffic. From the results shown in the table the following observations could be made:

- The resistance to compaction during construction (as estimated by the CEI) increases with the increase in FAA values for 28 of the 34 mixtures. The increase, measured relative to a mixture with FAA = 44, ranges from a low value of 1 % to a high value of 536 % pr unit change in FAA value. The average sample variance for CEI is estimated at 14 %. Thus for a change of FAA from 40 to 44, any change in CEI equal to or larger than 7 % per unit of FAA is considered statistically significant at 95 % probability. The results shown in Table 5.4 indicate that 23 mixtures out of the total 34 mixtures would require significantly more compaction effort to achieve density of 92 % Gmm.

- For the 6 mixtures that showed a decrease in CEI values the range is also significant and ranges between –4.0 % and –49 % per unit increase in FAA. It is important to notice that the decrease is shown only for source Y using the PG70-28 with both gradations. For this source when the PG 58-28 is used the results show a wide range of increase in CEI rather than a decrease with the exception of the mixture with high asphalt content and coarse (S-shaped) gradation. The results for this source are a good example of the highly interactive effects between FAA, asphalt content, asphalt grade, and gradation. The collective results for the CEI values show that in most cases the mixtures will be more resistant to compaction in the gyratory compactor when sands with higher values of FAA are used. It should be mentioned that the relationship of the CEI to field compaction is not known at this time.

- The changes in TEI values (resistance to densification under traffic) show a different trend compared to the CEI values. In 15 of the 34 mixtures the TEI values decrease by a significant amount when FAA is increased. The range in change of TEI is between 3 % and 98% per unit increase in FAA values. For a change in FAA from 40 to 44 the mixtures could lose as much as 360 % of the resistance to densification or distortion under traffic, as measured by the TEI. For the remaining mixtures there is an increase in the TEI ranging between 2 % and 54 % per unit increase in FAA. This trend indicates that for changing FAA from 40 to 44 the resistance to traffic could be increased by 200 %, which is very important change.

- While the increase in TEI is favorable, and follow the general concept that increasing FAA is favorable, the reduction in TEI values is very alarming because it could mean significant reduction in resistance to traffic. In addition it appears that there are very strong interactive factors that results in the absence of any well-defined trend. This lack of trend makes it unrealistic to set any criteria and any limits for controlling quality based on FAA values.

Table 5.3: Summary of Effect of Changing FAA by one unit on Volumetric Properties of Mixtures

Response Variables	FAA	Source = W						Source = X											
		PG Grade = 58-28			PG Grade = 70-28			PG Grade = 58-28						PG Grade = 70-28					
		G = Fine			G = Fine			G = Fine			G = S-Shaped			G = Fine			G = S-Shaped		
		AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%
%Gmm @ Nini	Per 1	-1.2	-1.0	-0.8	-1.6	-1.4	-1.1	-0.4	-0.4	-0.5	-0.3	-0.3	-0.4	-0.3	-0.3	-0.4	-0.2	-0.3	-0.3
%Gmm @ Ndes	Per 1	-0.6	-0.3	0.0	-1.0	-0.7	-0.4	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1
%Gmm @ Nmax	Per 1	-0.3	0.0	0.3	-0.8	-0.5	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1
VMA	Per 1	0.4	0.3	0.2	0.7	0.6	0.5	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0

Response Variables	FAA	Source = Y												Source Z				Extremes	
		PG Grade = 58-28						PG Grade = 70-28						PG Grade = 58-28		PG Grade = 70-28			
		G = Fine			G = S-Shaped			G = Fine			G = S-Shaped			G = Fine	G = S-Shaped	G = Fine	G = S-Shaped		
		AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt	AC = Opt	AC = Opt	AC = Opt	Low	High
%Gmm @ Nini	Per 1	-0.9	-0.3	0.4	-1.7	-1.1	-0.4	-0.7	-0.1	0.6	-1.5	-0.8	-0.2	-0.7	-0.7	-1.5	-1.5	-1.7	0.6
%Gmm @ Ndes	Per 1	0.1	0.2	0.2	-0.3	-0.2	-0.1	0.5	0.6	0.6	0.1	0.2	0.3	-0.4	-0.5	-1.0	-1.1	-1.1	0.6
%Gmm @ Nmax	Per 1	0.2	0.1	0.0	0.0	-0.1	-0.2	0.8	0.6	0.5	0.5	0.4	0.3	-0.2	-0.3	-0.9	-1.0	-1.0	0.8
VMA	Per 1	-0.3	0.0	0.3	-0.4	0.0	0.3	-0.7	-0.4	0.0	-0.7	-0.4	-0.1	0.5	0.3	1.0	0.7	-0.7	1.0

Table 5.4: Summary of Effect of Changing FAA by one unit on Change in CEI and TEI values of Mixtures Calculated as percent change relative to the values at FAA= 44

Response Variables	FAA	Source = W						Source = X											
		PG Grade = 58-28			PG Grade = 70-28			PG Grade = 58-28						PG Grade = 70-28					
		G = Fine			G = Fine			G = Fine			G = S-Shaped			G = Fine			G = S-Shaped		
		AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%
CEI	Per 1.0 unit	148	128	78	194	193	190	16	18	21	9	9	10	15	18	26	7	7	7
TEI	Per 1.0 unit	-6	-14	-39	2	0	-8	8	12	32	7	9	12	5	6	8	19	54	-56

Response Variables	FAA	Source = Y												Source Z				Extremes	
		PG Grade = 58-28						PG Grade = 70-28						PG Grade = 58-28		PG Grade = 70-28			
		G = Fine			G = S-Shaped			G = Fine			G = S-Shaped			G = Fine	G = S-Shaped	G = Fine	G = S-Shaped		
		AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt - 0.5%	AC = Opt	AC = Opt + 0.5%	AC = Opt	AC = Opt	AC = Opt	AC = Opt	Low	High
CEI	Per 1.0 unit	1	3	536	11	44	-22	-8	-13	-49	-4	-9	19	11	31	54	30	-49	536
TEI	Per 1.0 unit	-36	-34	-98	-28	2	-56	-24	-20	-14	-20	-14	-3	19	6	34	37	-98	54

5.3 Sensitivity Analysis for the Effect of Changing the Asphalt Content

To determine how sensitive the response variables are to changes in asphalt content, Equation 5.1, 5.2, 5.3, and 5.4 were solved for asphalt content = 1, 2, and 3 (optimum – 0.5, optimum, and optimum + 0.5) assuming three selected levels of FAA, two levels of gradation, and two levels of performance graded asphalt. Because of the relatively high interactive effects, the models were used for each combination of source, gradation, asphalt content, performance graded asphalt. Instead of looking at the overall average effect, the individual effects were calculated for the different combinations. Appendix I lists the results of this analysis.

The difference between the response variable for increasing the asphalt content by 0.5 were then calculated. Table 5.5 summarizes the asphalt content effects seen in Appendix I and lists the low and high range of each response variable.

Based on the results shown in Table 5.5 the following findings could be summarized:

1. The sensitivity of volumetric properties (% Gmm at Nini, Ndes, Nmax) to a 0.5 % increase in asphalt content appears to be highly source specific. Of particular behavior is source Y which shows a change of changes between 3.1 and 3.7 % Gmm at an FAA value of 48. The VMA sensitivity appear to also be source specific and to vary between an increase of 0.3 to a decrease of –2.7 % voids.

2. The sensitivity of % Gmm at Ndesign to 0.5 % change in asphalt content is also higher at higher FAA values. It ranges from 1. 0 % to 3.7 % Gmm at an FAA value of 48.

3. The changes in % Gmm at Nmax do not follow the same trend and show that for some mixtures increasing the FAA results in lower sensitivity to asphalt content.

4. The changes estimated are significant changes and are mostly higher than the estimated experimental variability estimated fro the volumetric properties. The results also indicate that increasing the FAA values could result in mixtures that are more sensitive to changes in asphalt content.

5. Comparing the effect of increasing the FAA (shown in Table 5.3) to the effect of increasing the asphalt content by 0.5 % (shown in Table 5.5), it could be seen that for source W changing FAA by one unit resulted in higher effects than changing asphalt content by 0.5 %, while changing FAA by two units will give changes that are equivalent to changing asphalt content by 0.5 %. In the case of source Y, The volumetric properties are much more sensitive to asphalt content than to FAA changes.

Table 5.5: Summary of Effect of Increasing Asphalt Content by 0.5 % on Volumetric Properties of Mixtures

Response Variables	AC	Source = W			Source = X						Source = Y						Extremes	
		PG Grade = 58-28			PG Grade = 58-28						PG Grade = 58-28							
		G = Fine			G = Fine			G = S-Shaped			G = Fine			G = S-Shaped			Low	High
		FAA			FAA			FAA			FAA			FAA				
		40	44	48	40	44	48	40	44	48	40	44	48	40	44	48		
%Gmm @ Nini	Increase of 0.5%	0.4	0.6	0.8	0.7	0.7	0.6	0.7	0.7	0.6	2.3	3.0	3.6	2.3	3.0	3.6	0.4	3.6
%Gmm @ Ndes	Increase of 0.5%	0.3	0.6	1.0	1.0	1.0	1.1	1.0	1.0	1.1	3.6	3.7	3.7	3.6	3.7	3.7	0.3	3.7
%Gmm @ Nmax	Increase of 0.5%	0.3	0.6	1.0	1.0	1.1	1.1	1.0	1.1	1.1	3.3	3.2	3.1	3.3	3.2	3.1	0.3	3.3
VMA	Increase of 0.5%	0.0	-0.1	-0.2	0.3	0.3	0.3	0.3	0.3	0.3	-2.7	-2.4	-2.1	-2.7	-2.4	-2.1	-2.7	0.3

Table 5.6 includes a summary of the effect of increasing asphalt content by 0.5 % on the construction and traffic indices (CEI and TEI). The following points summarize the observation that could be drawn from the results:

1. CEI values decreased for every combination of control variables with increasing the asphalt content. The decrease in CEI is expected because the lubricating effect of the additional asphalt. The range in reduction in CEI is between a low of 19 % to a high of 545 % calculated relative to the CEI estimated at the optimum asphalt content for each mixture. It is important to note that higher sensitivity to asphalt content change is seen at lower FAA values for all sources.

2. Compared to the effect of changing FAA (shown in Table 5.3, source W appears to be more sensitive to FAA changes than asphalt content changes, source X shows similar sensitivity to one unit change in FAA compared to 0.5 change in asphalt, while source Y is much more sensitive to asphalt content than one unit change in FAA.

3. TEI values decrease for every combination of control variables. This is also expected because less resistance to densification is expected with an increase in asphalt content. What is of interest is the trend of change with FAA; for sources W and X the mixtures are more sensitive to asphalt content at higher FAA values, while for source 3 the sensitivity to increasing asphalt content is less at higher values of FAA. Comparing the effects of changing FAA to changing asphalt content, sources W and X show that a minimum of two unit change in FAA could be similar to changing asphalt content by 0.5 %. Source Y results are mixed and appears to be more sensitive to 0.5 % change in asphalt content than a one or two unit changes in FAA

values, with the exception of changing FAA at high asphalt content (optimum + 0.5

%).

Table 5.6: Summary of Effect of Increasing Asphalt Content by 0.5% on CEI and TEI

of Mixtures

Response Variables	AC	Source = W PG Grade = 58-28 G = Fine FAA			Source = X PG Grade = 58-28						Source = Y PG Grade = 58-28						Extremes	
					G = Fine FAA			G = S-Shaped FAA			G = Fine FAA			G = S-Shaped FAA			Low	High
		40	44	48	40	44	48	40	44	48	40	44	48	40	44	48		
CEI	Increase of 0.5%	-145	-42	-55	-22	-20	-19	-19	-19	-19	-102	-99	-97	-545	-304	-211	-545	-19
TEI	Increase of 0.5%	-45	-55	-68	-42	-39	-36	-36	-34	-31	-108	-105	-100	-442	-315	-193	-442	-31

5.4 Sensitivity Analysis of Performance Graded Asphalt

To determine how sensitive the response variables are to changes in performance

graded asphalts, Equation 5.1, 5.2, 5.3, and 5.4 were solved for PG grade = 1, and 2 at all

three levels of asphalt content, and FAA and both levels of gradation, and performance

graded asphalt. Because of the relatively high interactive effects, the models were used for

each combination of FAA, gradation, asphalt content, performance graded asphalt. Instead

of looking at the overall average effect, the individual effects were calculated for the

different combinations. Appendix I lists the results of this analysis.

The difference between the response variable using the PG 70 –28 relative to using

the PG 58-28 were calculated. Table 5.7 summarizes the results for the volumetric properties

and lists the low and high range of each response variable. Table 5.8 lists the results for CEI

and TEI.

Table 5.7: Summary of Effect of Changing Performance Graded Asphalts from PG 58-28 to PG 70-28 on Volumetric Properties of Mixtures

Response Variables	FAA	Source = W			Source = X												
		AC = Opt			AC = Opt												
		G = Fine			G = Fine			G = S-Shaped									
		FAA			FAA			FAA									
		40	44	48	40	44	48	40	44	48							
%Gmm @ Nini	PG GRADE Change	1.7	0.2	-1.3	0.4	0.7	1.0	2.0	2.3	2.5							
%Gmm @ Ndes	PG GRADE Change	1.8	0.1	-1.5	-1.0	-0.7	-0.4	1.5	1.8	2.1							
%Gmm @ Nmax	PG GRADE Change	2.0	0.0	-2.0	-1.0	-0.8	-0.6	1.3	1.5	1.7							
VMA	PG GRADE Change	-6.6	1.2	7.7	6.1	5.5	4.9	3.3	2.8	2.3							

Response Variables	FAA	Source = Y						Source Z						Extremes	
		AC = Opt						AC = Opt							
		G = Fine			G = S-Shaped			G = Fine			G = S-Shaped				
		FAA			FAA			FAA			FAA				
		40	44	48	40	44	48	40	44	48	40	44	48	Low	High
%Gmm @ Nini	PG GRADE Change	-2.0	-1.1	-0.2	-2.0	-1.1	-0.2	3.7	0.5	-2.7	1.5	-1.7	-4.9	-5	4
%Gmm @ Ndes	PG GRADE Change	-3.6	-2.0	-0.4	-3.6	-2.0	-0.4	2.3	0.0	-2.3	1.2	-1.1	-3.4	-4	2
%Gmm @ Nmax	PG GRADE Change	-4.0	-1.9	0.2	-4.0	-1.9	0.2	2.2	-0.6	-3.3	1.7	-1.1	-3.9	-4	2
VMA	PG GRADE Change	20.2	10.9	1.6	23.4	12.8	1.8	-13.6	0.9	12.0	2.0	15.7	27.4	-13.6	27.4

Table 5.8: Summary of Effect of Changing Performance Graded Asphalts from PG 58-28 to PG 70-28 on CEI and TEI of Mixtures

Response Variables	FAA	Source = W			Source = X												
		AC = Opt			AC = Opt												
		G = Fine			G = Fine			G = S-Shaped									
		FAA			FAA			FAA									
		40	44	48	40	44	48	40	44	48							
CEI	PG GRADE Change	50	-8	31	-42	-42	-42	-43	-50	-54							
TEI	PG GRADE Change	-35	2	126	247	129	90	-131	-83	-59							

Response Variables	FAA	Source = Y						Source Z						Extremes	
		AC = Opt						AC = Opt							
		G = Fine			G = S-Shaped			G = Fine			G = S-Shaped				
		FAA			FAA			FAA			FAA			Low	High
		40	44	48	40	44	48	40	44	48	40	44	48		

CEI	PG GRADE Change	132	35	-43	-473	108	-52	-403	50	229	135	153	151	-473	229
TEI	PG GRADE Change	207	299	-301	1593	891	300	-541	189	283	-288	203	495	-541	1593

Based on the results shown in Tables 5.6 and 5.7 the following findings could be summarized:

1. The volumetric properties (% G_{mm} @ N_{init}, % G_{mm} @ N_{des}, % G_{mm} @ N_{max} and VMA) are sensitive to changing the PG grade. All changes with the exception of Source W at FAA=44 are more significant than one standard deviation of the average experimental error. The effects appear more significant at higher FAA value for sources W, X but are mixed for the other sources. There are highly interactive effects and changes vary between increase in % Gmm to decrease in % Gmm. No one trend can be generalized for the mixtures.

2. The range in changes due to replacing the PG 58 –28 with the PG 70-28 for % Gmm at Nini vary between a decrease of 4.9 % Gmm and an increase of 3.7 % Gmm. The range for % Gmm at N design is a decrease of 3.6 % and an increase of 2.1 %. The range for % Gmm at Nmax is similar to the changes for % Gmm at Ndes. VMA changes by a wider range.

3. The changes in CEI and CFI due to replacing the PG58 with the PG 70 are very significant, are highly mixture specific, and do not follow a single trend. The range for CEI is from a decrease of 473 % to an increase od 229%. The range in the change of the TEI values, although mostly positive, vary between a decrease of 541% to an increase of 1593%. These results indicate a significant interaction between PG grade and aggregate source. Also a significant interaction between PG grade and FAA

values. The interactions are so complex, there is hardly any trend that could be

identified that could define the effect of changing PG grade other than the observation

that the effects are much more significant than the experimental error which was

estimated at 14 % and 5 % for CEI and TEI, respectively.

4. The clear conclusion from this part of the study is that the PG grade change has a

pronounced effect of the volumetric and the densification properties of mixtures.

CHAPTER SIX

Summary of Findings and Conclusion

6.1   Summary of Findings

The objective of this research was to determine the effect of varying fine aggregate angularity, asphalt content, and performance grade of asphalts on performance-related properties of Hot Mix Asphalt (HMA) mixtures, as measured in the laboratory using the Superpave Gyratory Compactor. The experimental plan included testing aggregates from 4 different sources in Wisconsin and also included varying the gradation blend from each source to produce fine and coarse gradations. For each aggregate gradation, the angularity of the fine portion was varied by combining rounded, natural sand and angular manufactured sand at different proportions. The proportions were selected to cover the range of angularity commonly accepted in practice.   Also for each fine blend of aggregates, the asphalt content was changed from optimum to optimum – 0.5%, and optimum + 0.5%. The performance grading of the asphalt in the hot mix asphalt mixtures was changed from PG 58-28 to PG 70-28. It should be noted that the selection of the gradation included coarse gradations that passes under the restricted zone. Such gradations although recommended initially in the Superpave system, were shown in more recent studies to be unstable or tender (70). The results form the testing of mixtures with coarse gradations should not be therefore generalized to all coarse gradations.

Testing was conducted using the SGC to estimate volumetric properties and frictional resistance properties at different compaction efforts. The response variables included two sets of responses. One set was derived from the densification data collected from the SGC

and the other set was derived from the resultant force data collected with an additional device used within the SGC, known as the Gyratory Load Plate Assembly (GLPA). Response variables included two measures of work required to compact a mix during construction (CEI and CFI), two measures of work required to compact or distort the mix under traffic loading (TEI and TFI), and four measures of volumetric properties (% G_{mm} @ N_{init}, % G_{mm} @ N_{des}, % G_{mm} @ N_{max} and VMA).

The following sections include a summary of findings derived from the analysis of the results.

6.1.1 Effect of Fine Aggregate Angularity (FAA)

The results of this study confirm findings of earlier studies that showed varying the FAA has an important influence on critical properties of HMA mixtures. The effect is found to be highly dependent on the source of the aggregate, which indicates a strong interactive relationship between FAA and source.

Based on using the SGC results, the effect of FAA is found to be more important during the initial stages of compaction compared to the final stages for the majority of the blends tested in this study. It is also found that increase in FAA results in requiring higher work or force for compaction to 8 % air voids content, which is typical of the construction stage in the field. The increase in FAA also resulted in a significant increase, on the order of 2% to 6%, in air voids at the initial number of gyrations (N_{init}), which confirms that higher FAA will result in a mixture more resistant to compaction in the SGC.

The effect of FAA on the later stages of compaction (8 % air voids to 2% air voids) is not consistent for the blends tested. For two of the aggregate sources, increasing FAA resulted in increasing the traffic energy indices estimated based on densification and resultant force in the gyratory compactor, which could be an indication that these mixtures will be more resistant to densification or distortion under traffic. For the other two sources, however, increasing the FAA resulted in decreasing the traffic energy indices, which could be an indication that these mixtures are less resistant to densification or distortion under simulated traffic conditions. The lack of good correlation between fine aggregate angularity and performance of mixtures in which they are used is not new and has been reported before. In a recent study by Massad et. al, (72), it is pointed out that two previous studies , one by Huber et. al in 1998 (72) and another in 2000 by Fernandes et al. (73), have raised questions about the value of FAA. This lack of correlation was further analyzed in Masad's study by using imaging technique who indicated that indices that could distinguish between the aggregate shape, angularity and texture are needed. Massad's study, which included 22 aggregates and rutting resistance of mixtures in the Purdue wheel tracking device, under wet and dry conditions, concluded that angularity index showed the lowest correlation to number of passes to failure of mixtures while the texture index showed the best correlation. The texture index had a poor correlation ($R^2 = 0.34$ to 0.51) to the FAA value.

 The energy indicators during the later stages of construction are considered most important as they could relate to resistance to densification and distortion of mixtures under traffic loading. The decrease in these indicators was not expected since it is commonly known that increasing FAA should result in mixtures more resistant to deformation under traffic.

The results collected in this study indicate that increasing FAA results in increasing the energy required to compact mixtures in the SGC to 92 % Gmm while having a neutral or an adverse effect on energy required to resist densification from 92 % Gmm to 98 % Gmm. If these energy measures are proved to be related to compaction and traffic loading in the field, increasing FAA could mean complicating the construction process by requiring higher compaction effort while having a neutral, if not adverse effect on resistance to damage induced by traffic loading. This effect could be related to the manufactured sands used in this study or the change in volumetric properties resulting from exchanging the natural sands with manufactured sand. It could also be related to the type of aggregate gradations selected. Although the cause is not obvious, the trend in effects is believed to be alarming enough to require further evaluation before implementing a policy of requiring higher FAA values in the mixture design procedures. It appears that requiring a higher level of FAA will not always result in a better mixture and thus using a constant limit on FAA for all aggregate sources could be misleading. The interaction of FAA with other factors, such as coarse aggregate properties and asphalt content, is so important that unfavorable performance could result from an increased FAA value. A mechanical test on the total mixture, or a better analysis of the densification curve of a mixture such as the CEI and the TEI, is a better approach because it would include all interacting effects in the analysis as the final product is evaluated.

6.1.2   Effect of Asphalt Content (AC)

The results of this study indicate that varying the asphalt content has an important influence on critical properties of HMA mixtures, which include volumetric and frictional resistance of mixtures. The effect is found to be highly dependent on the source of the aggregate, which indicates a strong interactive relationship between asphalt content and source.   It should be mentioned here that experts in the field recognize that the effect of asphalt content could also be a function of HMA plant, aggregate breakdown, dust handling capability and variation between gradation in the design and in production.

The effect of asphalt content is found to be more important during the initial stages of compaction compared to the final stages for the majority of the blends tested in this study. It is also found that increase in asphalt content results in requiring significantly lower work or force for compaction to 8 % air voids content, which is typical of the construction stage in the field. The increase in asphalt content also resulted in a significant decrease, on the order of 2% to 6%, in air voids at the initial number of gyrations (N_{init}), which confirms that higher asphalt content will result in a mixture less resistance to compaction.

The effect of asphalt content on the later stages of compaction (8 % air voids to 2% air voids) is not consistent for the blends tested. For all of the aggregate sources, increasing asphalt content resulted in decreasing the traffic energy indices estimated based on densification and resultant force in the gyratory compactor.

The energy indicators during the later stages of construction are considered most important as they relate to resistance to densification and distortion of mixtures under traffic loading. The decrease in these indicators was expected since it is commonly known that increasing asphalt content should result in mixtures less resistant to deformation under

traffic. The results indicate that the new parameters selected (CEI and TEI) are sensitive to asphalt content and follow the known trend of changes. Because of this sensitivity, they show the potential of complimenting the volumetric properties in selecting a mixture design that would result in good performance.

6.1.3   Effect of Performance Grade of the Asphalt (PG Grade)

The results of this study indicate that varying the performance grade of the asphalt has an important influence on certain critical properties of HMA mixtures. The effect is found to be highly dependent on the source of the aggregate for certain properties (%G_{mm} @ N_{ini}, %G_{mm} @ N_{max}, VMA), which indicates a strong interactive relationship between performance grade of the asphalt and source.

The effect of the performance grade is found to be more important during the final stages compared to the initial stage for the majority of the blends tested in this study. The increase in the performance grade resulted in a marginal increase, on the order of 2% to 6%, in air voids at the initial number of gyrations (N_{init}), which confirms that a higher performance grade asphalt could result in a mixture more resistant to compaction.

The effect of the performance grade of asphalt on the later stages of compaction (8 % air voids to 2% air voids) is not consistent for the blends tested. The effect depends highly on the gradation type and also the FAA values. No clear trend could be identified and the changes range from 541 % reduction to 1500 % increase in the TEI. Also the change in % Gmm at N max varied significantly between a reduction of 4 % Gmm to an increase of 2 % depending on gradation, source and FAA values.

The energy indicators during the later stages of construction are considered most important as they relate to resistance to densification and distortion of mixtures under traffic loading. The decrease in these indicators was not expected since it is commonly known that increasing performance graded asphalt should result in mixtures more resistance to deformation under traffic. Because of the inconsistent trends in these indices measured in this study, it is recommended that actual testing of the mixture with the selected asphalt be conducted and that the selection be based on the results of CEI, TEI, and volumetrics.

6.1.4   Role of Aggregate Source

The effect of source on the response variables was significant for each of the responses measured or estimated from the SGC measurements. In particular, source of aggregate showed a significant effect on resultant force required during early stages of compaction and the air voids at design number of gyrations (N_{des}). This finding suggests that the influence of source properties is important at all stages of compaction and could have effects on construction and resistance to traffic loading.

6.1.5   Role of Aggregate Gradation

Gradation was found to have the least influence on the response variables considered in this study, with the exception of the Voids in the Mineral Aggregates (VMA). The S-shaped blends were not shown to perform significantly differently than fine blends when the densification and the energy indices were compared. There were, however, important interactions between gradation and source. This indicates that gradation is still an important consideration in predicting mixture performance but the influence is highly source and

angularity specific. The effect on VMA is logical and was expected due to the fact that gradation controls the voids directly.

6.2 Recommendations

The following are the major recommendation of this research:

1.)   The results of this study do not support the requirement for the FAA in the specifications. The findings of this study, which are based on laboratory testing only, show the effect of FAA to be highly dependent on the source of the aggregate. Therefore, unless the FAA requirement is coordinated with the source of the aggregate the performance of the asphalt mixtures will not likely improve.

2.)   The results do not support allowing asphalt content to vary in the range of + / - 0.5% optimum asphalt content for performance indices due to the significant decrease in resistance to traffic when optimum + 0.5% asphalt content is used. Therefore the recommendation is to reduce the allowable limit in the optimum asphalt content from + / - 0.5% to + / - 0.3%. This needs to be confirmed with additional research regarding the acceptable range.

3.)   The findings of the study indicate that mixtures with PG 70-28 is very source specific, and can increase or decrease the resistance to compaction or traffic depending on the source. Therefore this study does not support the bumping of grades unless the resistance to traffic can be shown using the TEI or TFI.

4.)   Due to the very high R^2 values for the correlation between the construction indices and traffic indices, the recommendation is made to only use the CEI and TEI since these indices can be measured from the SGC without any additional equipment.

5.)   Limits for the construction and traffic indices were recommended using the database created by the UW-Madison Asphalt Group using mix designs used by various contractors and compacted in the UW-Madison asphalt laboratory.   The recommended limits for the construction indices (CEI, and CFI) are 250, and 350 respectively. The recommended limits for the traffic indices (TEI, and TFI) are 1000, and 2500 respectively.

6.3   Conclusions

The following are the major conclusions of this research:

1.)   The results of this study do not support the assumption that higher values of FAA would always result in better performing mixtures. The findings of this study show the effect of FAA to be highly dependent on the source of the aggregates. It is, therefore, difficult to suggest a limit on FAA independent of the source that would improve quality of asphalt mixtures. This finding challenges some important guidelines used today in the mixture design practice. Because of the relatively small size of experiment conducted and the use of new devices to evaluate mixtures, more elaborate research is recommended before any change in practice is implemented.

2.)   The findings indicate that mixtures with fine aggregates of high FAA values are more difficult to compact in the SGC than those with low FAA values. It is not known if this trend measured in the SGC would be seen in the field. It is therefore necessary to conduct field studies before a change in specification could be recommended.

3.)   The results of this study do not support the assumption that a range of + / - 0.5% range is acceptable for performance indices due to the significant decrease in resistance to traffic when optimum + 0.5% asphalt content is used.

4.)   The findings of the study indicate that the effect of replacing a PG58-28 with a PG

70-28 could be highly source specific, and can increase or decrease the resistance to

densification or distortion under as measured by the SGC in the laboratory. This challenges

the current practice of increasing binder grade for better traffic resistance for all aggregate

sources. The finding should therefore be verified in the field or with more mixture

performance testing in the laboratory to ensure it is not an artifact of the SGC testing method.

6.4   Suggestions for Future Research

It is suggested that future research increase the number of sources studied. Source

was found to be the primary interacting factor with FAA, but there is not a clear relationship

between the two. It is suggested that the focus of any future research on this topic be

directed towards confirming the results collected from the Gyratory compactor with actual

mixture performance testing by measuring rutting and fatigue cracking. It is also important

to verify the results of the resistance to compaction in the field.

REFERENCES

1.)   O. D. Boutilier. A Study of the Relation Between the Particle Index of the Aggregate and the Properties of Bituminous Aggregate Mixtures. Proc., AAPT, Vol. 33, 1967, pp. 157-179.

2.)   E. R. Brown and S. A. Cross "A National Study of Rutting in Hot Mix Asphalt Pavements." NCAT Report 92-5. National Center for Asphalt Technology, 1991.

3.)   J. W. Button, D. Perdomo, and R. L. Lytton. "Influence of Aggregate on Rutting of Asphalt Concrete Pavements." Transportation Research Record 1259. Transportation Research Board, Washington D.C. 1990. pp 141-152.

4.)   R. J. Cominsky. The Superpave Mix Design Manual for New Construction and Overlays. Strategic Highway Research Program. National Research Council. Washington D.C. 1994.

5.)   S. A. Cross and E. R. Brown. "Selection of Aggregate Properties to Minimize Rutting of Heavy Duty Pavements." Asphalt Mixture Performance, Richard C. Meininger, Editor. ASTM STP 1147. 1992.

6.)   S. A. Cross, B. J. Smith, and K. A. Clowers Evaluation of Fine Aggregate Angularity Using National Aggregate Association Flow Test. Transportation Research Record 1437.

7.)   C. R. Foster. Dominant Effect of Fine Aggregate on Strength of Dense-Graded Asphalt Mixes. Special Report 109. HRB, National Research Council, Washington, D.C., 1970, pp. 1-3.

8.)   J. E. Gray and J. E. Bell. Stone Sand. National Crushed Stone Association Engineering Bulletin 13, 1964.

9.)   J. M. Griffith and B. F. Kallas, Aggregate Voids Characteristics in Asphalt Paving Mixes. HRB Proc., Vol. 36, 1957.

10.)   J. M. Griffith and B. F. Kallas. Influence of Fine Aggregate on Asphaltic Concrete Paving Mixtures. HRB Proc., Vol. 37, 1958, pp. 219-255.

11.)   M. Guler and H. U. Bahia "Development of a Device For Measuring Shear Resistance of HMA in the Gyratory Compactor."

12.)   M. Herrin and W. H. Goetz. Effect of Aggregate Shape on Stability of Bituminous Mixes. HRB Proc., Vol. 33, 1954.

13.)	G. A. Huber, J. C. Jones, P. E. Messersmith and N. M. Jackson Contribution of Fine Aggregate Angularity and Particle Shape to Superpave Mixture Performance. <u>Transportation Research Record</u> 1609.

14.)	I. Ishai and E. Tons. A Concept and a Test Method for a Unified Characterization of the Geometric Irregularity of Aggregate Particles. <u>ASTM Journal of Testing and Evaluation</u>, Vol. 5, No. 1, 1977.

15.)	I. Ishai and E. Tons. Aggregate Factors in Bituminous Mixture Design. Report 335140-1-F. University Of Michigan, Ann Arbor, Mich., 1971.

16.)	I. Ishai and H. Gelber. Effect of Geometric Irregularity of Aggregates on the Properties and Behavior of Bituminous Concrete. <u>Proc</u>., AAPT, Vol. 51, 1982.

17.)	R. R. Lottman and W. H. Goetz. <u>Effect of Crushed Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures</u>. Circular 63, National Sand Gravel Association, 1956.

18.)	I. V. Kalcheff and D. G. Tunnicliff. Effects of Crushed Stone Aggregate Size and Shape on Properties of Asphalt Concrete. <u>Proc</u>., AAPT, Vol. 51, 1982.

19.)	P. S. Kandhal and F. Parker Jr., "Aggregate Tests Related to Asphalt Concrete Performance in Pavements." NCRP Report 405 National Academy Press Auburn, AL 1998.

20.)	P. S. Kandhal,, M. A. Khatri, and J. B. Motter. "Evaluation of Particle Shape and Texture of Mineral Aggregates and Their Blends." In <u>Proceedings</u>; Vol. 61, Association of Asphalt Paving Technologists, 1992.

21.)	P. S. Kandhal, J. B. Motter, and M. A. Khatri. "Evaluation of Particle Shape and Texture: Manufactured verses Natural Sands." Transportation Research Record 1301, TRB, NCAT Report 91-3 National Research Council, Washington, D.C. 1991.

22.)	G. R. Laughlin. <u>Limestone Fine Aggregate in Portland Cement Concrete</u>. Highway Research Laboratory, Lexington, Ky., 1960.

23.)	C. Lee, C. Pan and T. D. White. Review of Fine Aggregate Angularity Requirements in Superpave. Purdue University, West Lafayette, Indiana, USA.

24.)	G. W. Maupin. Effect of Particle Shape and Surface Texture on the Fatigue Behaviour of Asphaltic Concrete. In <u>Highway Research Record 313</u>, HRB, National Research Council, Washington, D.C., 1970, pp. 55-62.

25.)	W. R. Meier, Jr., E. J. Elnicky, and B. R. Schuster. "Fine Aggregate Shape and Surface Texture." FHWA – A288-229. DOT Arizona, Lansing. 1979

26.)   R. C. Meininger. "Proposed Method of Test for Particle Shape and Texture of Fine Aggregate Using Uncompacted Void Content." National Aggregate Association, Silver Spring, MD 1990.

27.)   <u>Method of Determining Voids Content, Flow Time, and percentage Oversize Material in Sand.</u> Des. C121-69. Central Laboratories, New Zealand Ministry of Works, Wellington, 1969.

28.)   R. B. Moore and R. A. Welke. <u>Effects of Fine Aggregate on Stability of Bituminous Mixes</u>. Research Report 78 TB-34-79F, Testing and Research Division, Testing Laboratory Section, Michigan Department of Transportation, 1979.

29.)   F. Parker and E. R. Brown. "Effects of Aggregate Properties on Flexible pavement Rutting in Alabama." <u>Asphalt Mixture Performance</u>, Richard C. Meininger, Editor. ASTM STP 1147. 1992.

30.)   F. Parker and E. R. Brown. "Effects of Asphalt Concrete Properties on Flexible Pavement Rutting in Alabama, Effects of Aggregate and Mineral Fillers on Asphalt Performance." ASTM STP 1147 Richard C. Manning (ed). American Society for Testing and Materials, Philadelphia, 1992.

31.)   H. M. Rex and R. A. Peck. "A Laboratory Test to Evaluate the Shape and Texture of Fine Aggregate Particles." Public Roads, Vol 20, Num 5. Dec. 1956.

32.)   <u>Road and Bridge Specifications</u>. Virginia Department of Highways, Richmond, 1970.

33.)   F. L. Roberts, P. S. Kandhal, E. R. Brown, D. Lee, and T. W. Kennedy <u>Hot Mix Asphalt Materials, Mixture Design, and Construction</u>. Second Edition. NAPA Education Foundation Lanham, Maryland. 1996.

34.)   C. A. Sanders and E. L. Dukatz. "Evaluation of Percent Fracture of Hot Mix Asphalt Gravels in Indiana." <u>Asphalt Mixture Performance</u>, Richard C. Meininger, Editor. ASTM STP 1147. 1992.

35.)   E. Shklarsky and M. Livneh. The Use of Gravels for Bituminous Paving Mixtures. <u>Proc., AAPT</u>, Vol. 33, 1964.

36.)   M. Stroup-Gardiner, D. Newcomb, W. Kussman, and R. Olson. "Characteristics of Typical Minnesota Aggregates" Transportation Research Record 1583. Aggregates, Filler, and Reutilized Materials in Asphalt Mixtures.

37.)   K. D. Stuart, and W. S. Moganor. "Evaluation of Natural Sands Used in Asphalt Mixtures." FHWA-RD-93-070. Transportation Research Record 1436 Federal Highway Administration, U.S. DOT, McLean, VA, June 1993.

38.)   Tentative method of Test for Uncompacted Void Content of Fine Aggregate. National Sand and Gravel Association and National Ready-Mix Concrete Association, Washington, D.C., Undated.

39.)   "The Method for Measuring Fine Aggregate Angularity." Michigan Test Method. 119-90. DOT – Michigan, Lansing, 1990.

40.)   E. Tons and W. H. Goetz. Packing Volume Concept for Aggregates. In Highway Research Record 236, HRB, National Research Council, Washington, D.C., 1968.

41.)   P. A. Wedding and R. D. Gaynor. The Effects of Using Crushed Gravel as the Coarse and Fine Aggregate in Dense Graded Bituminous Mixtures. Proc., AAPT, Vol 30, 1961.

42.)   E. L. Dukatz, "Aggregate Properties Related to Pavement Performance." Proceedings of the Association of Asphalt Paving Technologists. Volume 58, 1989.

43.)   German Supplemental Technical Specifications and Guidelines on Asphalt Surface Coarses, ZTVbit S&B 84, Der Bundesminister, FGR, Verkehr, 1990.

44.)   National Crushed Stone Association, "Proposed Method of Test for Voids in Individual Size Fractions of Manufactured Stone Sand Fine Aggregate For Concrete." Unpublished.

45.)   Boutilier, O. D., "A Study of the Relation Between the Particle Index of Aggregate and the Properties of Bituminous Aggregate Mixtures." Association of Asphalt Paving Technologists. Volume 33, 1967.

46.)   F. Field. The Importance of Percent Crushed in Coarse Aggregate as Applied to Bituminous Pavements. Proceedings, AAPT. Vol 27, 1958.

47.)   B. E. Gaudette and R. A. Welke. Investigation of Crushed Aggregates for Bituminous Mixtures. Michigan Department of State and Highway Transportation. Report No. TB-58, 1977.

48.)   R. R. Lottman and W. H. Goetz. Effect of Crushed Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures. National Sand and Gravel Association Circular No. 63, 1956.

49.)   R. G. Hicks, S. Albright, and J. R. Lundy. "Evaluation of Percent Fracture and Gradation on Behavior of Asphalt Concrete and Aggregate Base." By the Transportation Research Institute, Oregon State University, Corvallis, OR.

50.)   E. L. Dukatz, "Materials Selection and Mix Design for Municipal Use." Presentation at the 2nd Annual International Roads and Bridges Maintenance and Rehabilitation Conference, Atlanta, GA, 14 October, 1988.

51.)   A. Gronhaug, "Evaluation and Influence of Aggregate Particle Shape and Form." Norwegian Research Laboratory, Oslo, Norway, Medd. N.R. 31.

52.)   "Report of the AASHTO Joint Task Force on Rutting" American Association of State Highway and Transportation Officials, Washington, D.C. February, 1989.

53.)   Tim Aschenrener, "Implementation of a Fine Aggregate Angularity Test", Colorado Department of Transportation. April, 1994.

54.)   James S. Lai. "Development of a Simplified Test Method to Predict Rutting Characteristics of Asphalt Mixes." Georgia Department of Transportation.

55.)   Hussain U. Bahia, Timothy P. Friemel, Pehr A. Peterson, Jeffrey S. Russell, and Brian Poehnelt. "Optimization of Constructibility and Resistance to Traffic: A New Design Approach for HMA Using the Superpave Compactor" Journal of the Association of Asphalt Paving Technologists, Volume 67, pp. 189-232.

56.)   Neter, John, Wasserman, William, and Kutner, Michael H. Applied Linear Statistical Models. 2nd Edition. Richard D. Irwin, Inc. Homewood Illinios, 1985.

57.)   Nordheim, Erik V. and Murray, Clayton K. Course Notes for Statistics /   Forestry / Horticulture 571 Department of Statistics, University of Wisconsin, Madison. July 30, 1997.

58.)   FAA Study (Fine Aggregate Angularity) File #S: 257-2189-96 & 257-2009-98 Wisconsin Department of Transportation – Bureau of Highway Construction Truax Center Laboratory, Madison Wisconsin 1996 & 1998.

59.)   Anderson, Michael R., Cominsky, Ronald J., and Killingsworth, Brian M. "Sensitivity of Superpave Mixture Tests to Changes in Mixture Components" Journal of the Association of Asphalt Paving Technologists, Volume 67, pp. 152-187.

60.)   Qi, Xicheng, Sebaaly, Peter E., and Epps, Jon A. "Evaluation of Polymer-Modified Asphalt Concrete Mixtures" Journal of Materials in Civil Engineering, May 1995. pp. 117-124

61.)   Epps, Amy L., and Hand, Adam J. "Coarse Superpave Mixture Sensitivity" Transportation Research Record 1712. Transportation Research Board, Washington D.C. 2000. pp. 35-43.

62.)   Sebaaly, Peter E., Ridolfi Dan, Gangavaram, Raja S., and Epps, Jon A. "Selecting Most Desirable Hot-Mix Asphalt Mixtures" Transportation Research Record 1590. Transportation Research Board, Washington D.C. 1997. pp. 99-107.

63.)   Kamel, Nabil I., and Miller, Laverne J. "Comparative Performance of Pavement Mixes Containing Conventional and Engineered Asphalts" Transportation Research Record 1454. Transportation Research Board, Washington D.C. 1994. pp. 172-180.

64.)   Zhou, Haiping, Nodes, Scott E., and Nichols, James E. "Evaluation of Three Polymer Modified Asphalt Concretes" Transportation Research Record 1454. Transportation Research Board, Washington D.C. 1994. pp. 181-192.

65.)   Kandhal, Prithvi S., and Cross, Stephen A. "Effect of Aggregate Gradation on Measured Asphalt Content" Transportation Research Record 1417. Transportation Research Board, Washington D.C. 1993. pp. 21-28.

66.)   Farrar, Mike, Harvey, Rick, Ksaibati, Khaled, and Ramanasundaram Bhaskar "Performance of Binder-Modifiers in Recycled Asphalt Pavement: Field Trial, 1987 to 1992" Transportation Research Record 1417. Transportation Research Board, Washington D.C. 1991. pp. 64-73.

67.)   Stuart, Kevin D. "Asphalt Mixtures Containing Chemically Modified Binders" Transportation Research Record 1417. Transportation Research Board, Washington D.C. 1994. pp. 74-83.

68.)   State of Wisconsin, Department of Transportation, " Supplemental Specifications," amending the 1996 Edition of the Standard Specifications for Highway and Structure Construction, 2000 Edition.

69.)   Guidelines and Methodologies for the Rehabilitation of Rigid Pavements using HMA overlays. Pavement Consulting Services. Draft Report to National Asphalt Pavement Association. December 1989.

70.)   Masad, E; Button, JW; Papagiannakis, T, Fine-Aggregate Angularity : Automated Image Analysis Approach, Transportation Research Record - Journal of the Transportation Research Board 1721, 2000, pp 66-72.

71.)   Dr. Ervin Dukatz, Mathy Construction Company , Private Communications.

72.)   Huber, G.A., J. C. Jones, P.A. Messersmith, and N.M. Jackson. Contribution of Fine Aggregate Angularity and Particle Shape To Superpave Mixture Performance. In Transportation Research Record 1609, TRB, National Research Council, Washington, D.C., 1998, pp. 28-35.

73.)   Fernandes, J.L., R. Roque, M. Tia, and L. Casanova,. Evaluation of Un-compacted Void Content of Fine Aggregate as a Quality Indicator of Materials Used in Superpave Mixtures. Presented at the 79th Annual Meeting of the Transportation Research Board ,TRB, Washington, D.C., 2000.

74.)   Massad, E., D. Olcott, T. White, and L. Tashman. Correlation of Fine Aggregate Imaging Shape Indices with Asphalt Mixture Performance, Transportation Research Record 1757, TRB, National Research Council, Washington, D.C., 2001, pp. 148-156.